JÜLICH
FORSCHUNGSZENTRUM

Remarks on a Johann spectrometer for exotic-atom research and more

Detlev Gotta[1] **and Leopold M. Simons**[2]

[1]*Institut für Kernphysik, Forschungszentrum Jülich, Germany*

[2]*Laboratory for Particle Physics, Paul Scherrer Institut, Switzerland*

CSI 2015

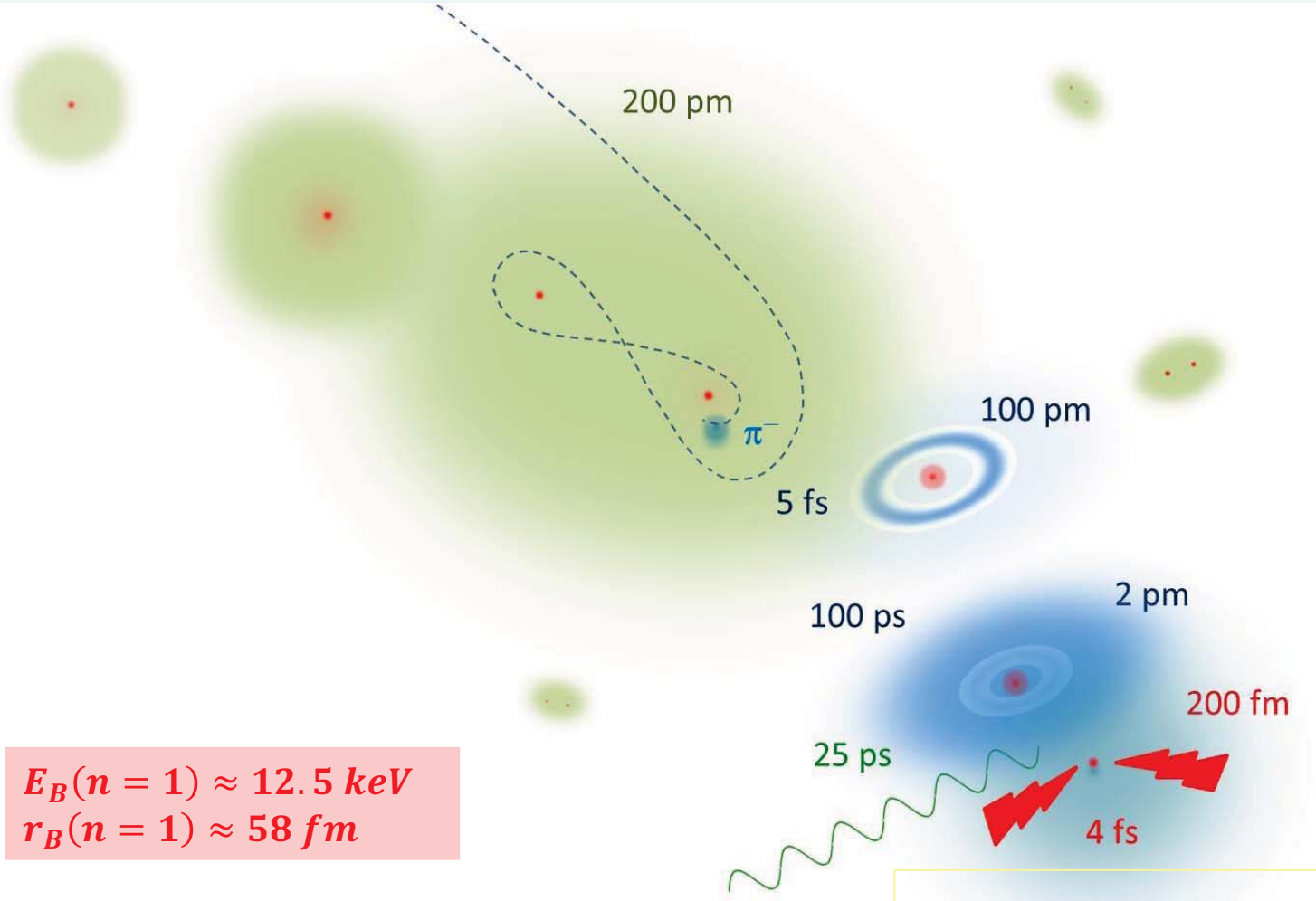
Figueira da Foz, August 31, 2015

MOTIVATION

MEASUREMENT OF PHOTONS ≈ *2 – 10 keV*

- ***from***
  - ***Exotic atoms*** $\mu A, \pi A, \bar{p}A$ $A = A(Z,N)$
  - ***Electronic atoms***
- ***Energy determination to ≈ ± 10 meV***
- ***Choice: Johann-type crystal spectrometer***

PIONIC OR ANTIPROTONIC HYDROGEN

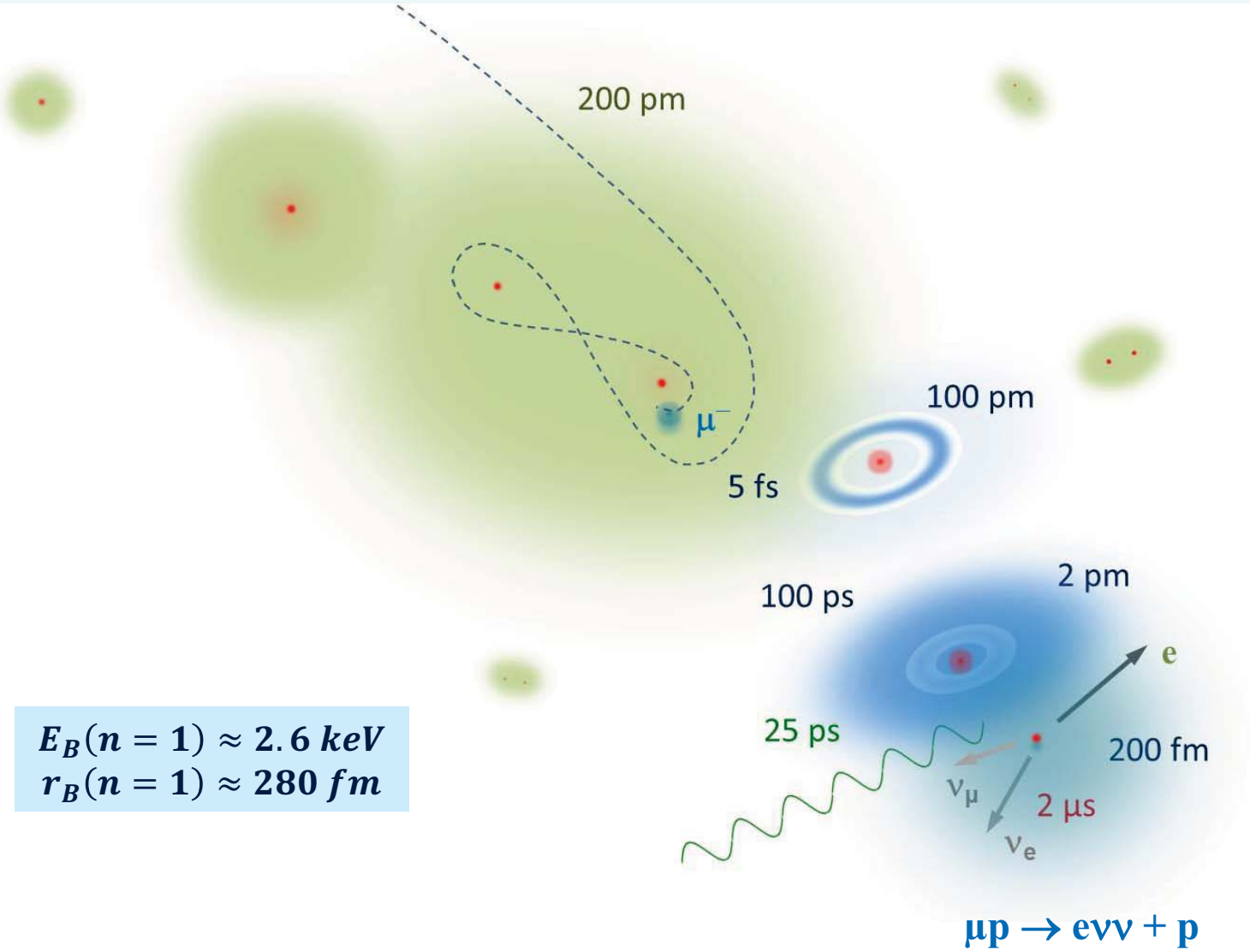


$E_B(n=1) \approx 12.5\ keV$
$r_B(n=1) \approx 58\ fm$

$\pi p \rightarrow \pi^0 + n / \gamma + n$

$\bar{p}p \rightarrow 5.5\ \pi$ in average

MUONIC HYDROGEN



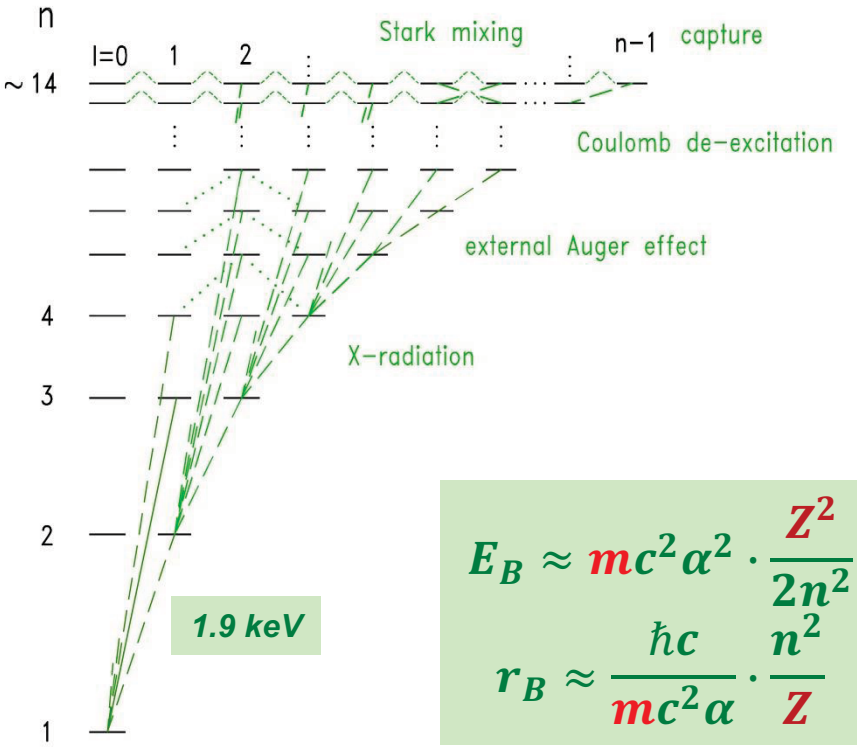
$$E_B(n=1) \approx 2.6\ keV$$
$$r_B(n=1) \approx 280\ fm$$

$$\mu p \rightarrow e\nu\nu + p$$

EXOTIC ATOMS - ORDERS OF MAGNITUDE

μH

only QED and finite-size effects

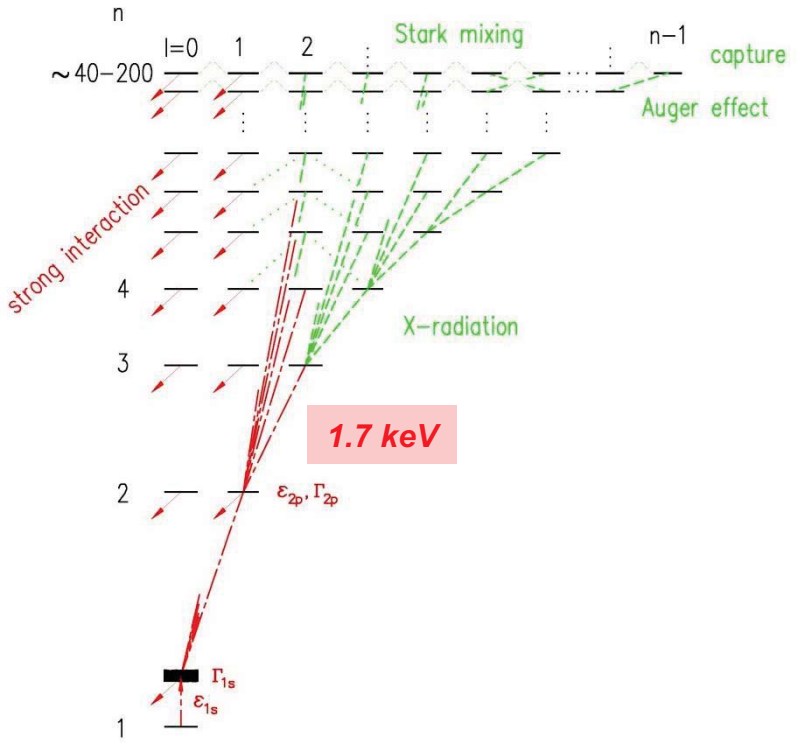


$$E_B \approx mc^2\alpha^2 \cdot \frac{Z^2}{2n^2}$$

$$r_B \approx \frac{\hbar c}{mc^2\alpha} \cdot \frac{n^2}{Z}$$

$\bar{p}$H

QED, finite size and strong interaction effects



DEMANDS

- **„keep“ plane crystal resolution**

  quartz and silicon crystals $\left(\frac{\lambda}{\Delta\lambda} \approx 10^4\right)$

- **low rates**

  10 -100 / hour while 10^6 $\bar{p}$ and 10^8 π^- / second

- **together with severe background conditions**

  decay and annihilation

GEOMETRY

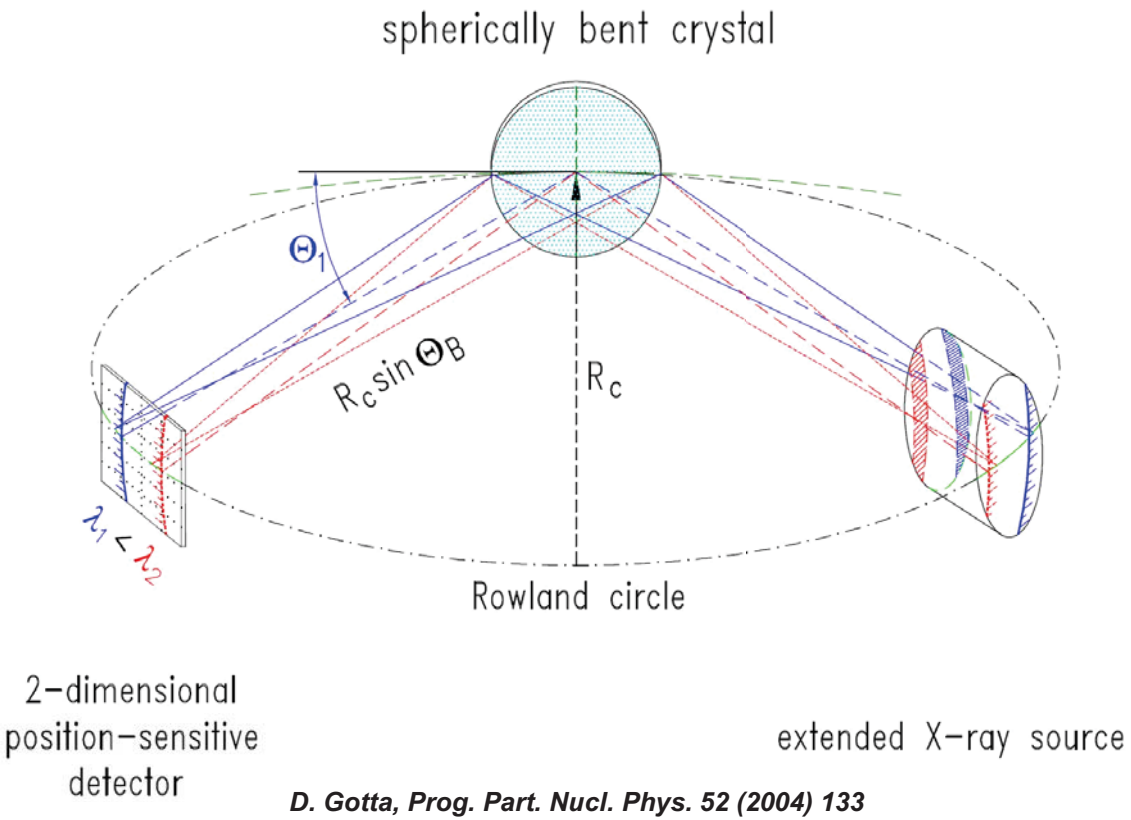
SET-UP

EXAMPLES

GEOMETRY

GEOMETRY WITH SPERICALLY BENT CRYSTALS

extended Bragg law $n\lambda = 2d \cdot \left[1 - \left(\frac{2d}{n\lambda}\right)^2 \delta\right] \cdot sin\Theta_B$



D. Gotta, Prog. Part. Nucl. Phys. 52 (2004) 133

focussing conditions

horizontal $R_c \cdot sin\Theta_B$ ✓

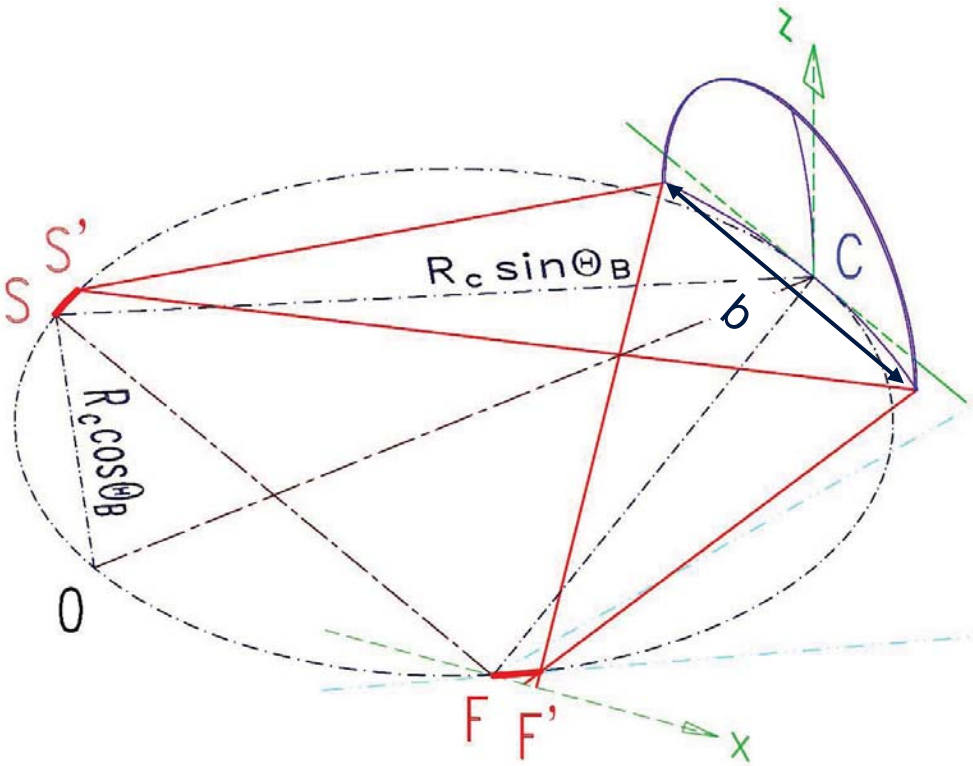
vertical $R_c \cdot sin^2\Theta_B$

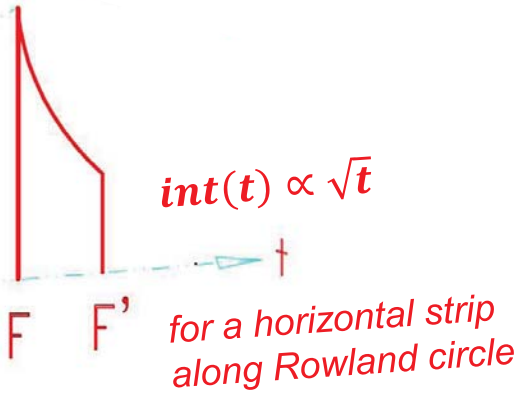
usually dismissed

angular dispersion

sym. plane $\frac{dE}{d\Theta} = -\frac{E}{tan\,\Theta_B}$

GEOMETRY - SYMMETRY PLANE





for a horizontal strip along Rowland circle

Johann defocussing

$$\Delta\Theta_J = \frac{1}{2} \cdot \left(\frac{b}{2R_C}\right)^2 \cot\Theta$$

$\overline{\Delta\Theta_J} \approx \frac{1}{3} \cdot \Theta_J^{max}$ *cyl. crystal*

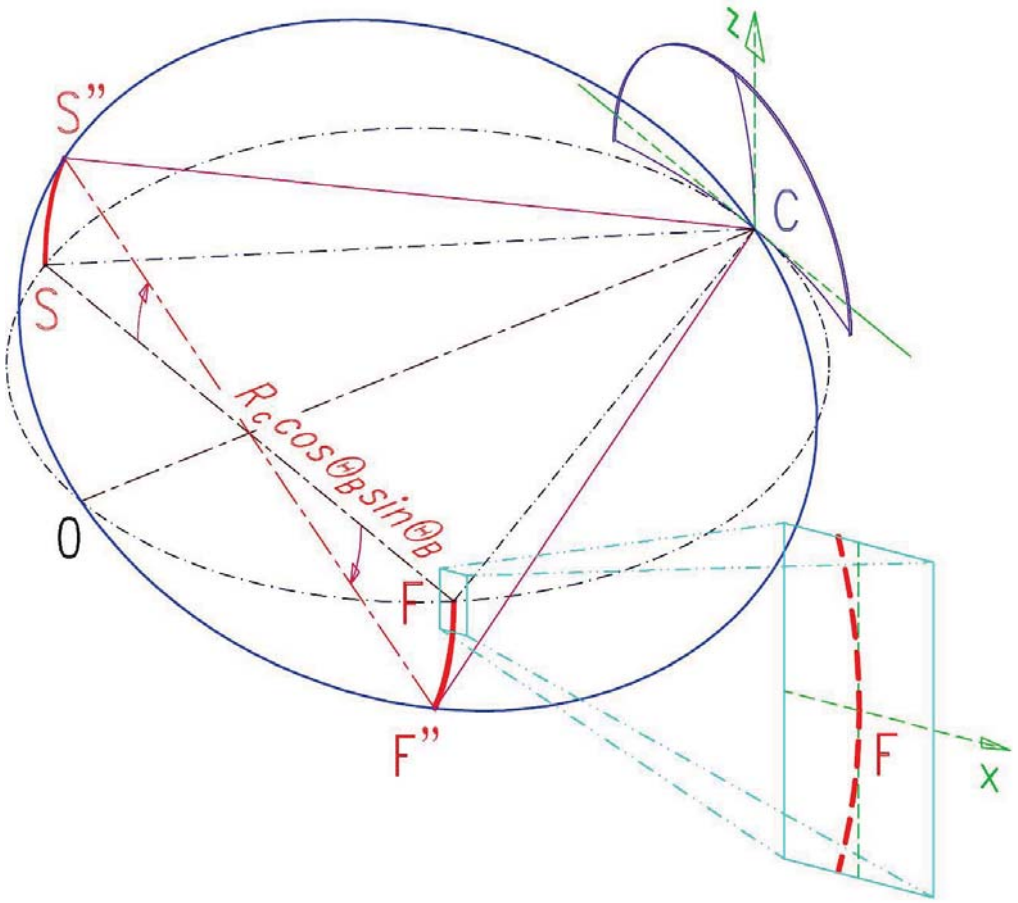
$\overline{\Delta\Theta_J} \approx \frac{1}{4} \cdot \Theta_J^{max}$ *spher. crystal*

x: ***detector plane*** $\perp \overline{CF}$

dispersion $\frac{dE}{dx} = \frac{dE}{d\Theta} \cdot \frac{1}{R_c \cdot \sin\Theta_B}$

H.H.Johann, Z. Phys, 69 (1931) 185
T. Johansson, Z. Phys. 82 (1933) 507

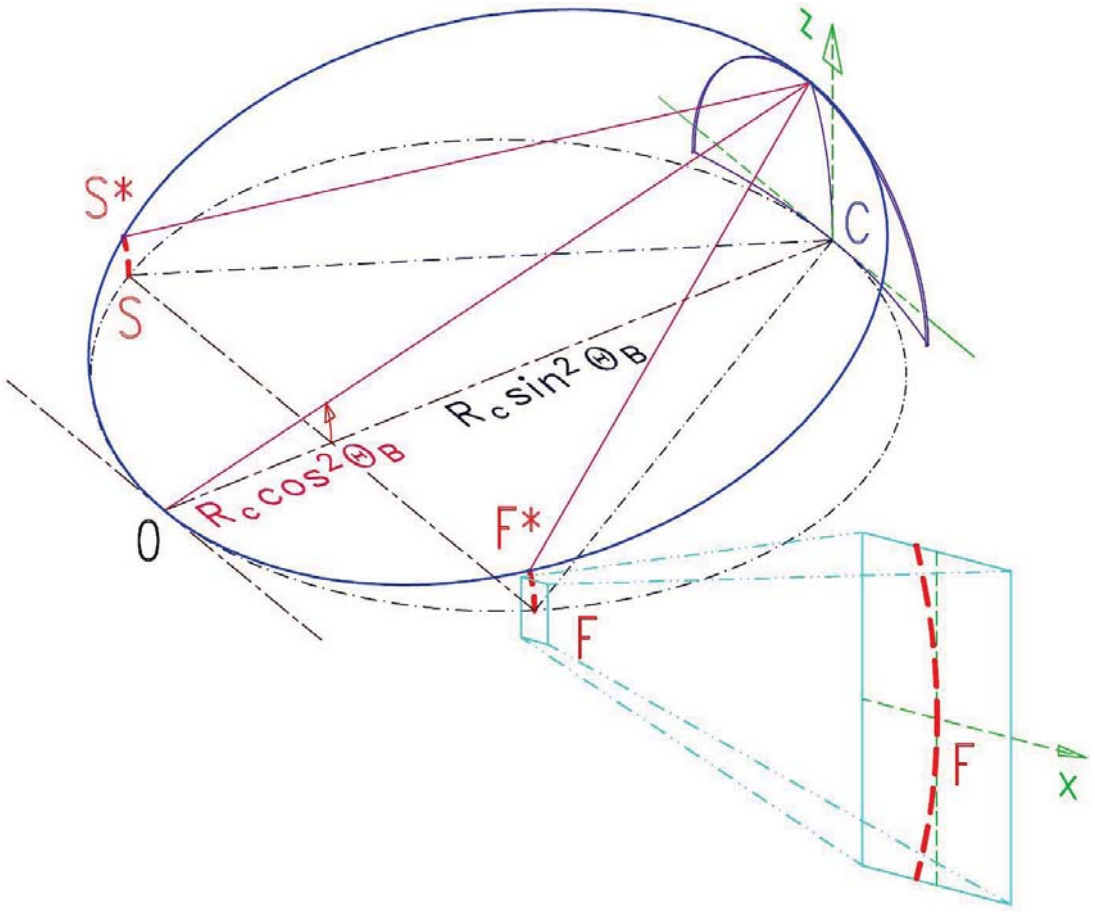
GEOMETRY - ROTATIONAL SYMMETRY $\overline{OC}$



radius of arc in detector plane

$$r_{apex} = R_c \cdot cos\Theta_B$$

GEOMETRY - ROTATIONAL SYMMETRY $\perp \overline{OC}$

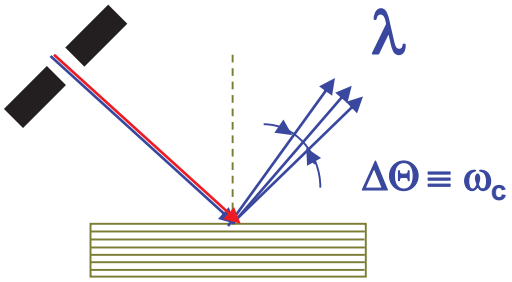


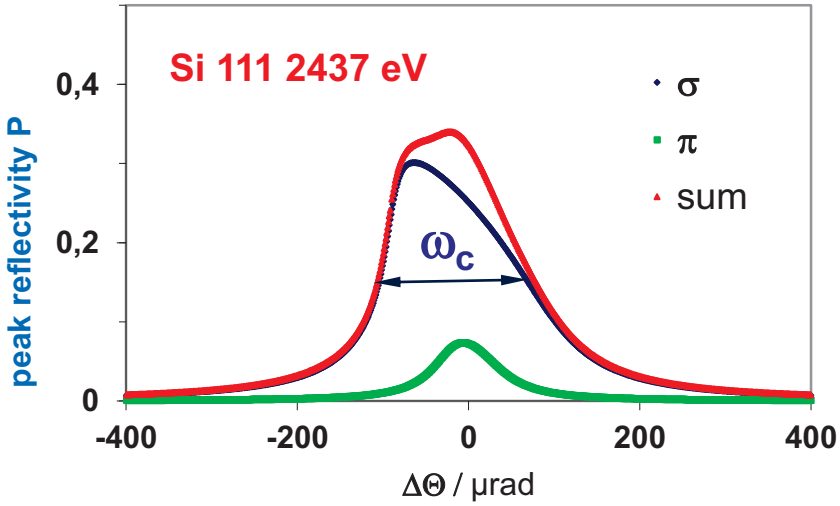
radius of arc in detector plane

$$r_{apex} = R_c \cdot cos\Theta_B$$

PLANE CRYSTAL - INTRINSIC RESOLUTION

ω_c angular spread of „diffraction“ :rocking curve





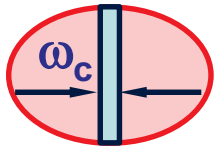
calculated by using XOP:
M.Sanchez del Rio and R.J.Dejus
SPIE proc. vol. 5536 (2004) 171

THUMB RULES FOR REFECTION CONTROL

apex curvature $r_{apex} = R_c \cdot \cos \Theta_B$

rate estimate $\eta = \frac{\Delta\Omega}{4\pi} \cdot P \cdot \frac{\Delta S}{S} \cdot \frac{H_{detector}}{H_{reflection}}$

$\frac{\Delta S}{S} = fraction\ of\ source\ area$

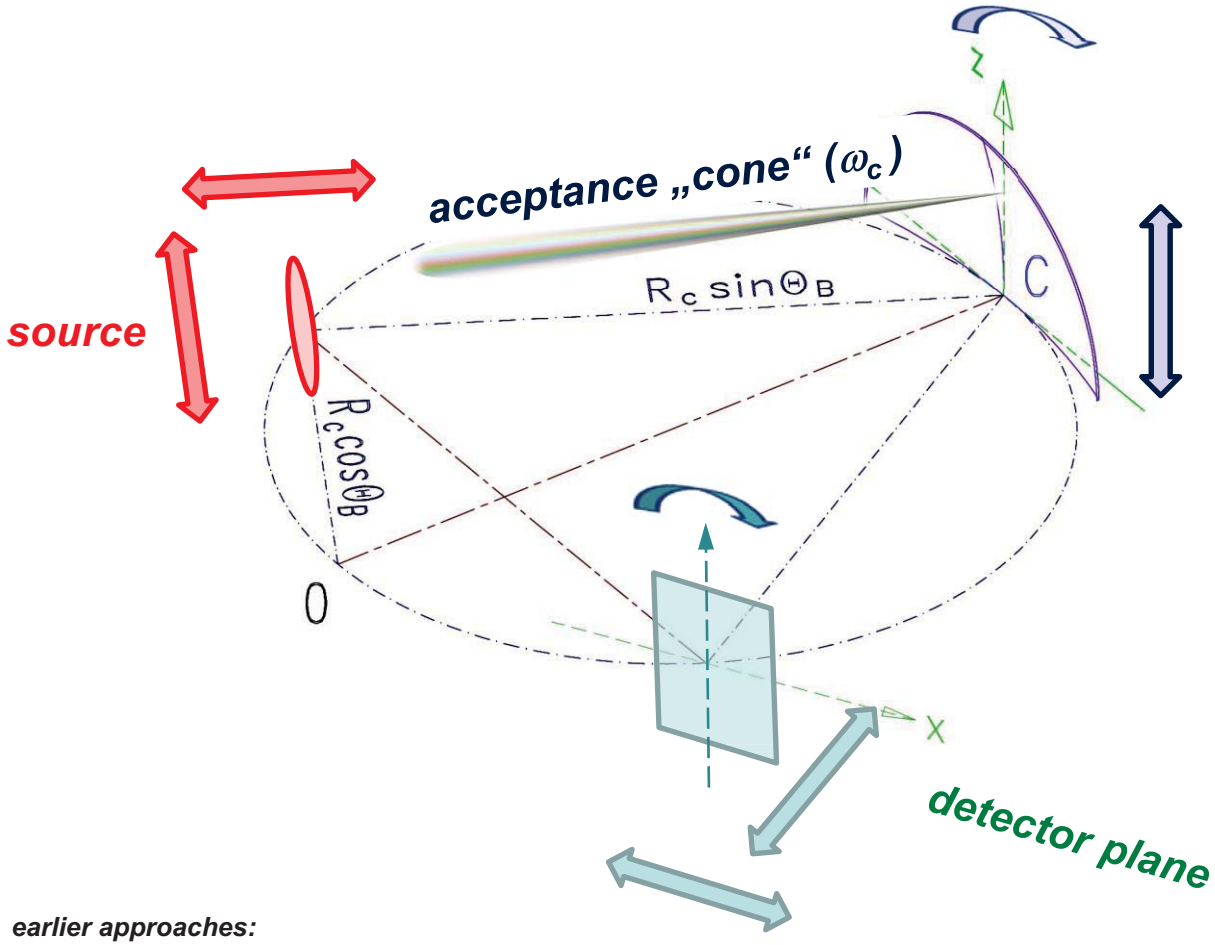


resolution $\sqrt{\omega_c^2 + \overline{\Delta\Theta_J}^2} \leq \Delta\Theta_{exp} \leq \omega_c + \overline{\Delta\Theta_J}$

$\omega_c \geq\cong 2 \cdot \overline{\Delta\Theta_J}$

RAY TRACING

L.M. Simons: program XTRACK



θ_G: glancing angle

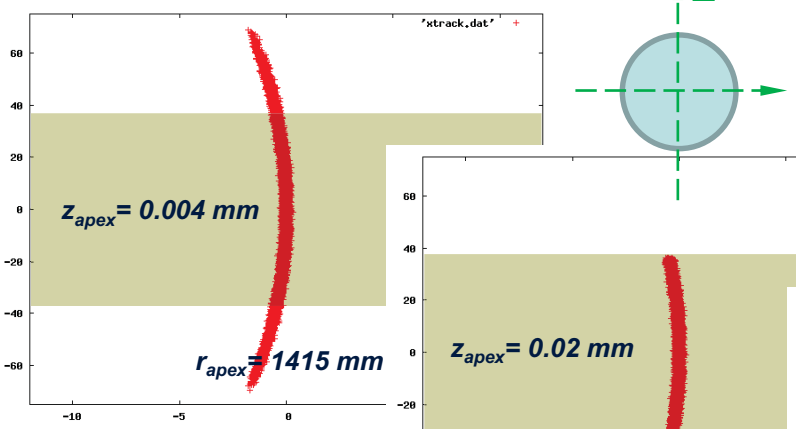
angle interval on crystal surface for a fix point (of the source)

$$\omega_c \approx \theta_G$$

earlier approaches:
H.F.Beyer and D.Liesen, Nucl.Instr.Meth A272(1988)895
S.Morita. Jap.J.Appl.Phys. 22(6) (1983)1030
G.Zschornack, G. Müller, G.Musiol, Nucl.Instr.Meth. 200(1982)481
...

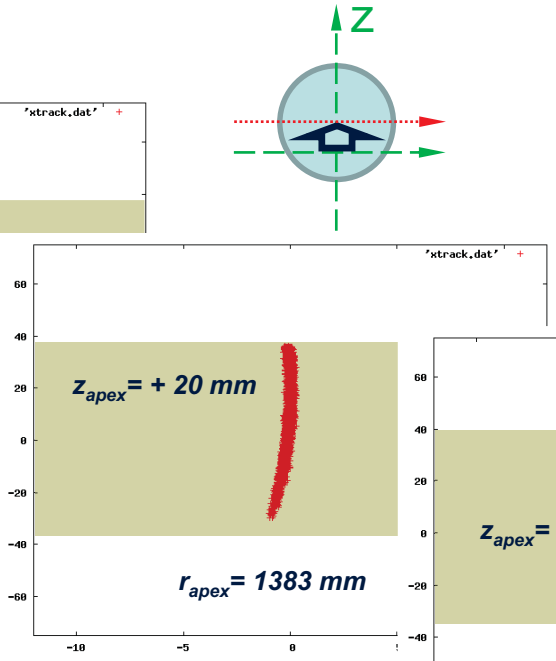
for an „analytical“ discussion of spherically bent mirrors, see, e.g., J. Eggs and K. Ulmer, Z. angew. Phys. 20 (1965) 118

RAY TRACING - EXAMPLE *μH(3p-1s) 2.249 keV*

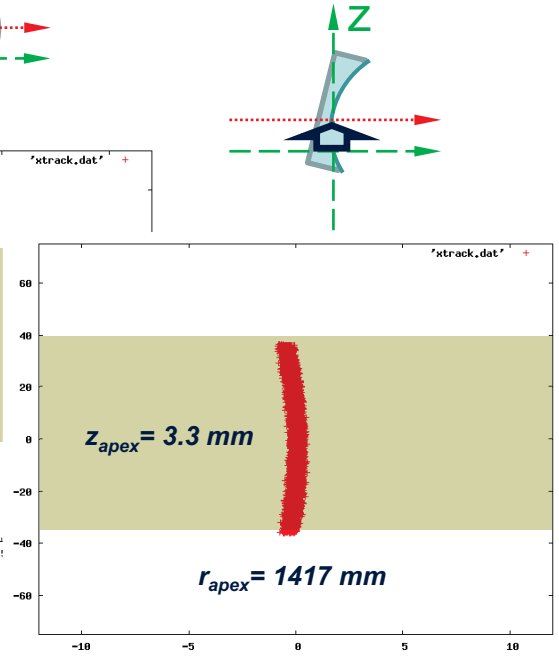


- *source ϕ100 mm*
- *no detector limit*

- *source ϕ100*
- *detector limit*
  H x V = 24 x 72 mm



- *source ϕ100*
- *detector limit*
- *crystal + 20 mm*



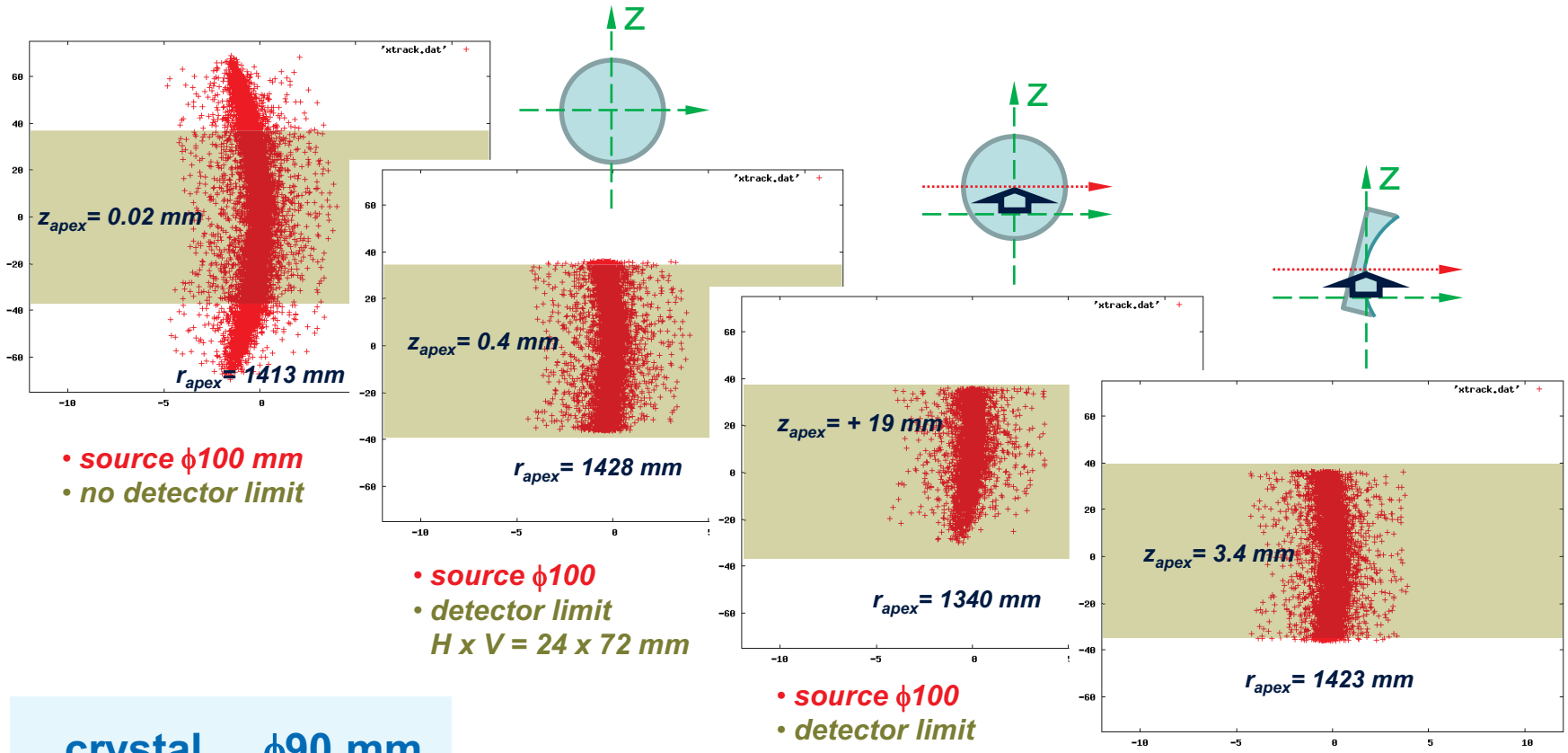
- *source ϕ100*
- *detector limit*
- *crystal + 20 mm*
- *crystal tilt -0.45°*

crystal ϕ90 mm

δ - response

Θ_B = 61.5°
R_c = 2982 mm
r_{apex} = 1422 mm

RAY TRACING - EXAMPLE *μH(3p-1s) 2.249 keV*

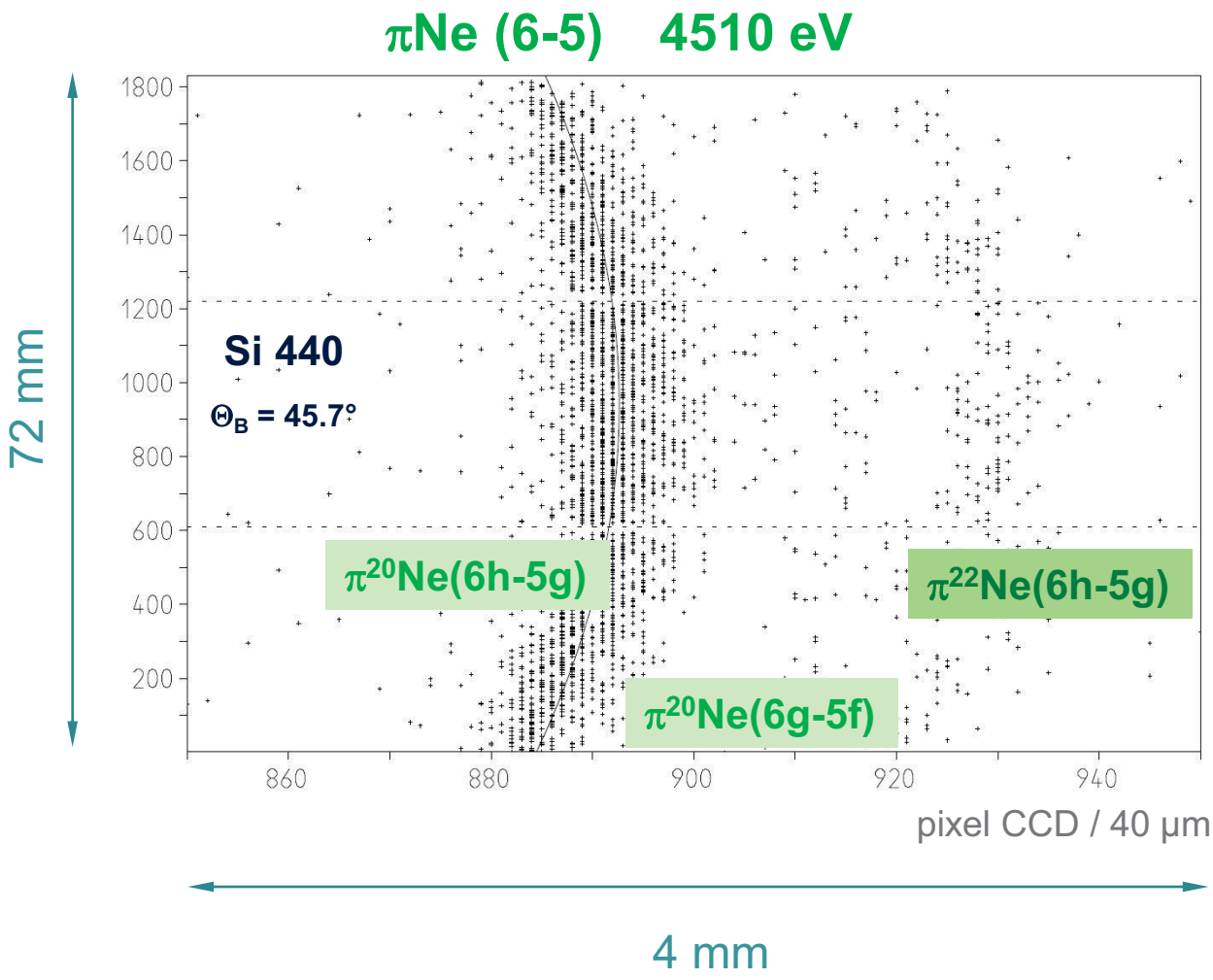


crystal ϕ90 mm

Si 111 - response

Θ_B = 61.5°
R_c = 2982 mm
r_{apex} = 1422 mm

HIT PATTERN → ENERGY SPECTRUM



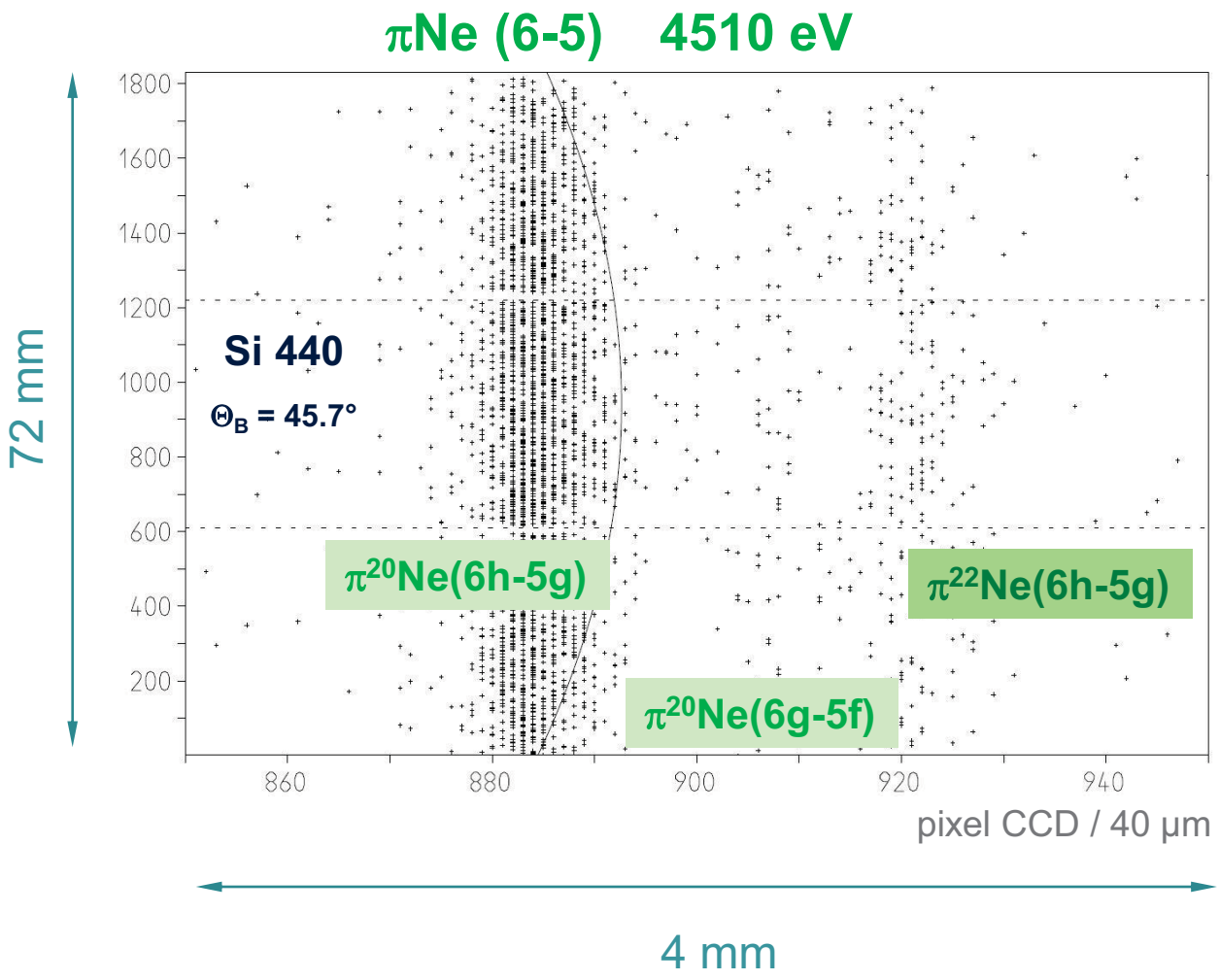
Curvature: parabola fit

radius in apex:

$R_c \cdot \cos \Theta_B = 2082\ mm$

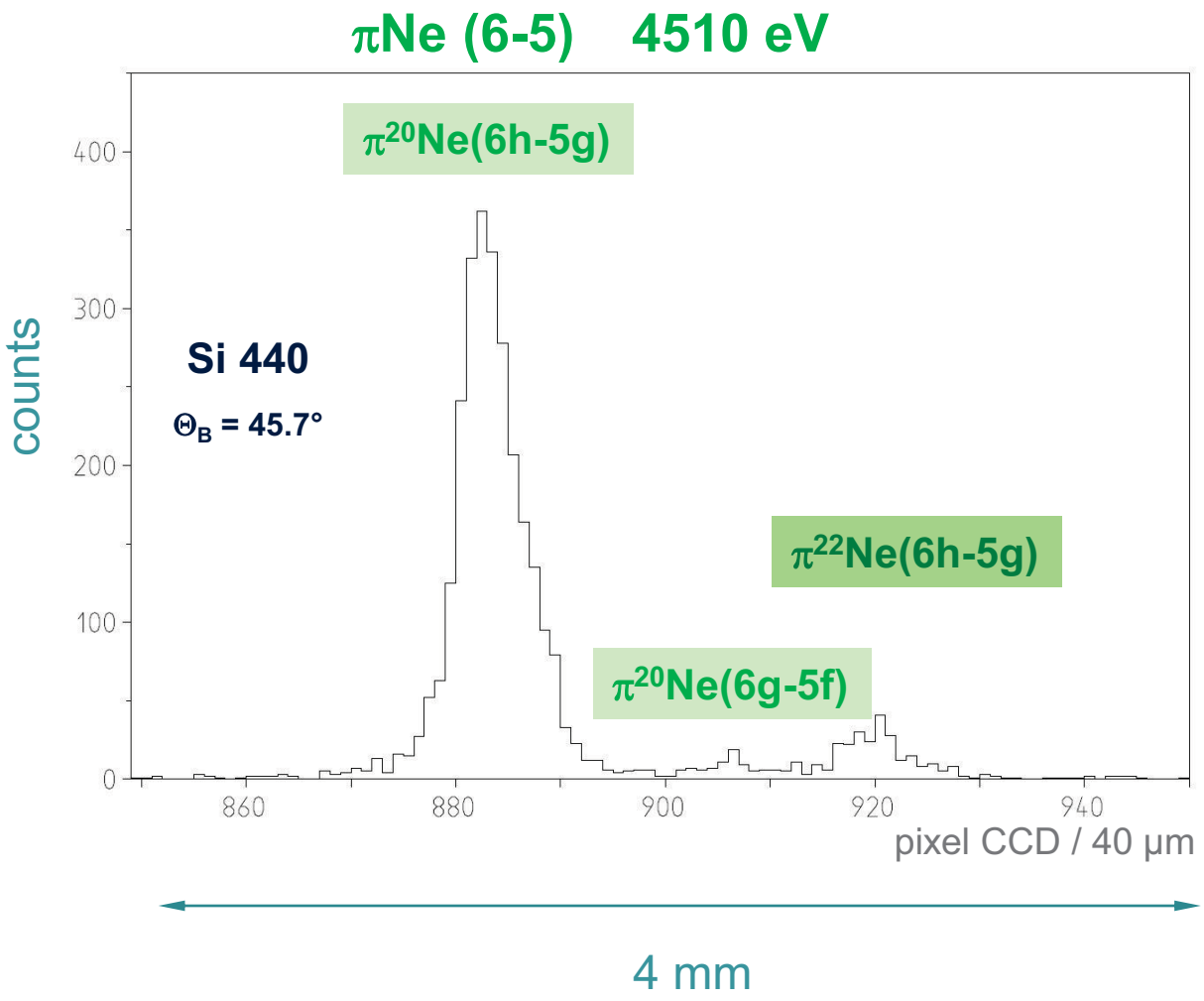
MC	$2041 \pm 5\ mm$
Exp.	$1897 \pm 70\ mm$

HIT PATTERN → ENERGY SPECTRUM



curvature corrected

HIT PATTERN → ENERGY SPECTRUM



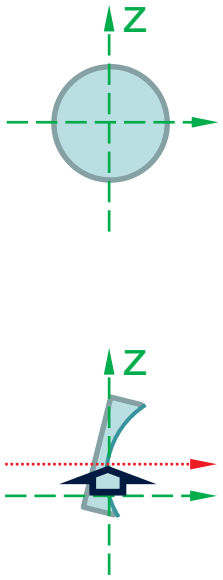
projection

onto

axis of dispersion

1 pixel = 82 meV

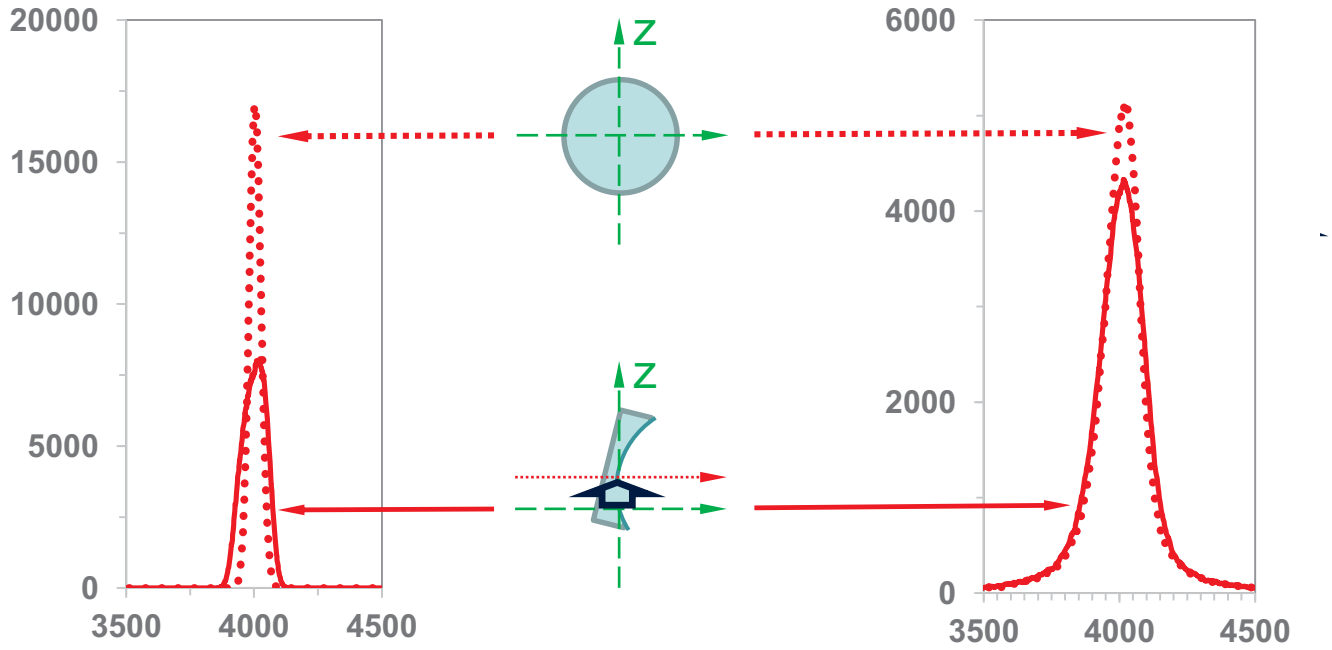
POSSIBLE MISALIGNMENTS - 1: CRYSTAL SET-UP



Si 111 - response

δ - response

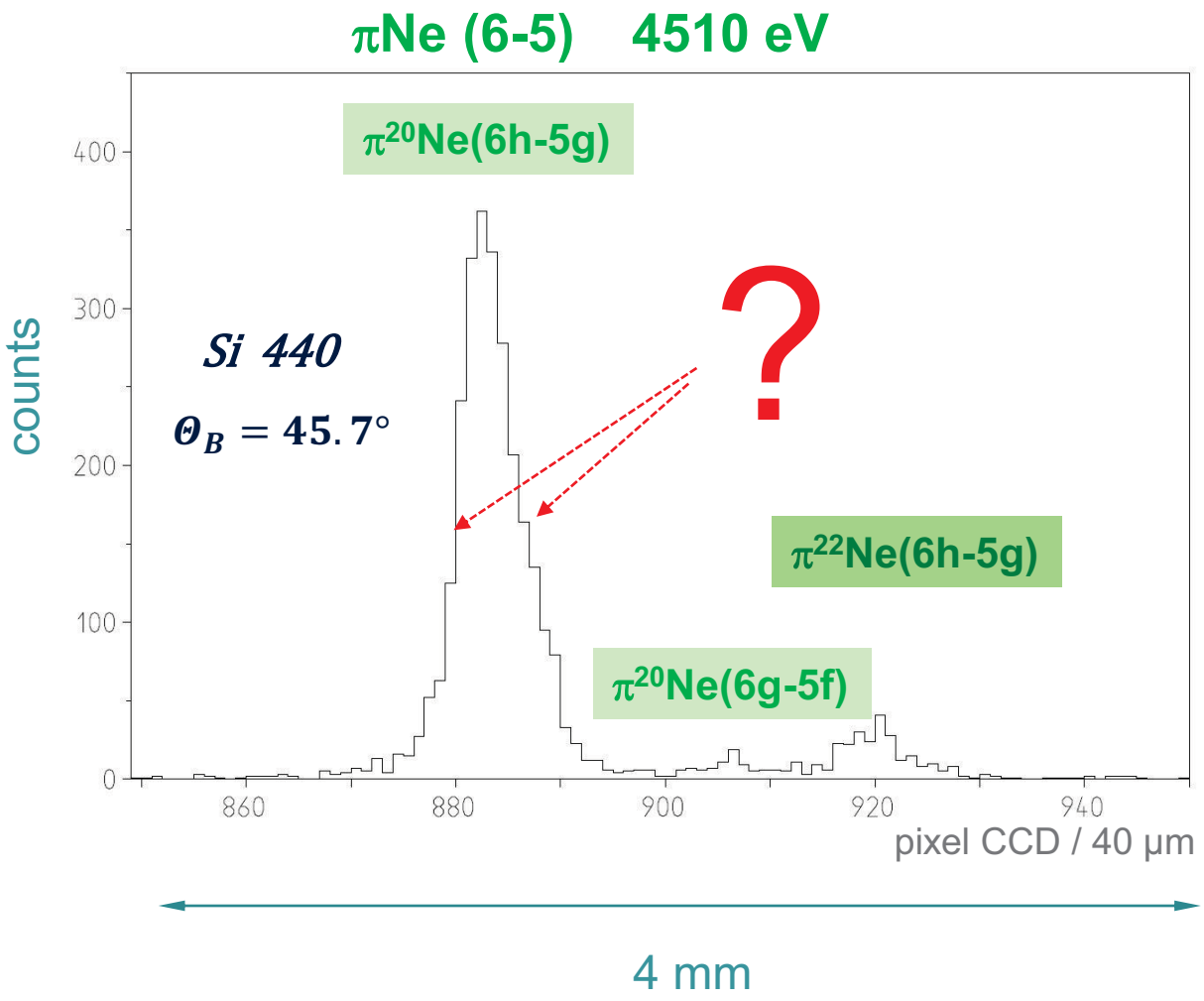
POSSIBLE MISALIGNMENTS - 1: CRYSTAL SET-UP



Si 111 - response

δ - response

POSSIBLE MISALIGNMENTS - 2: FOCAL LENGTH



projection

onto

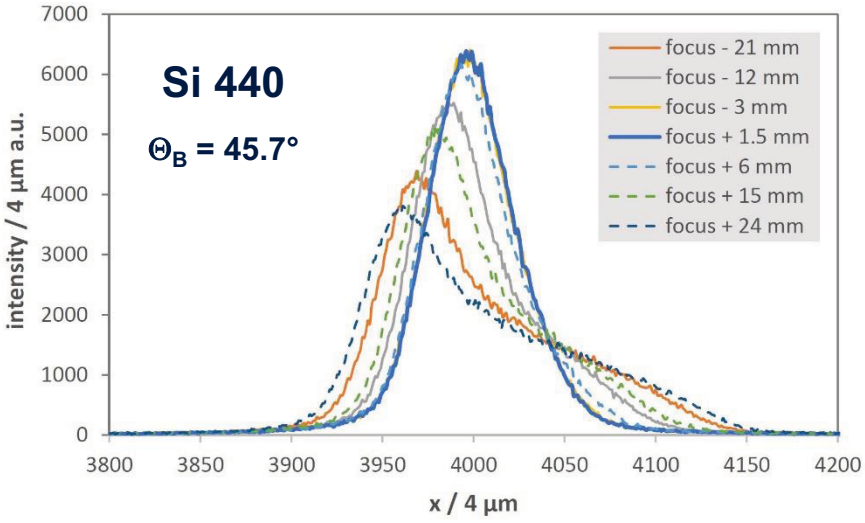
axis of dispersion

1 pixel = 82 meV

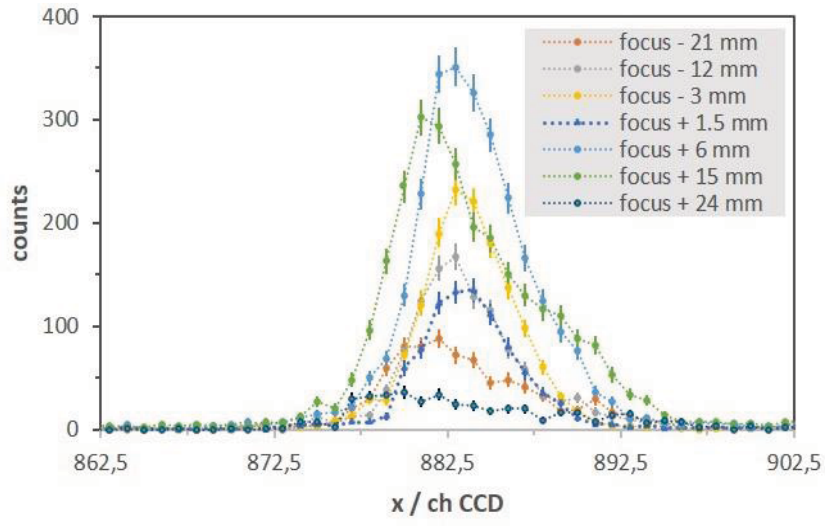
POSSIBLE MISALIGNMENTS - 2: FOCAL LENGTH

πNe (6h-5g) 4510 eV

MC simulation



data



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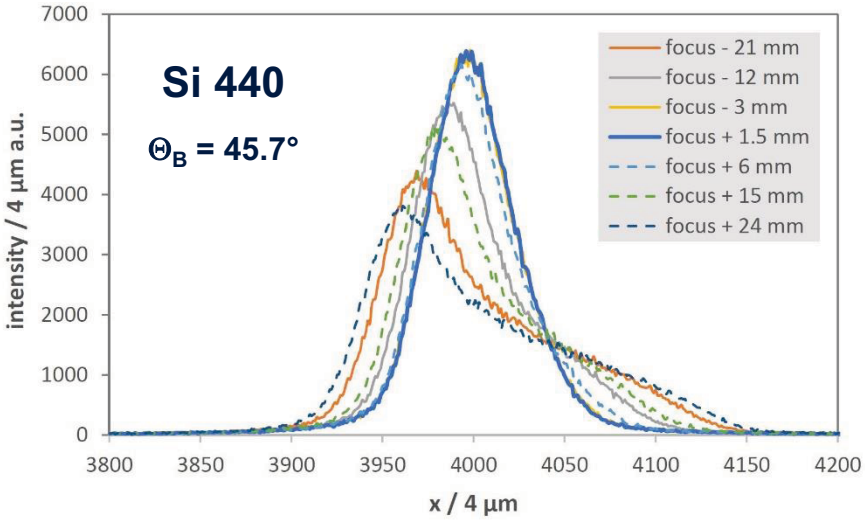
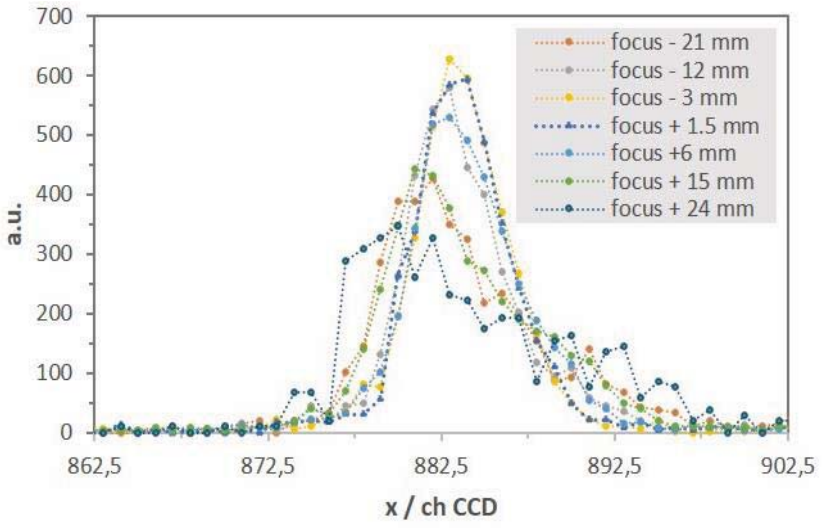
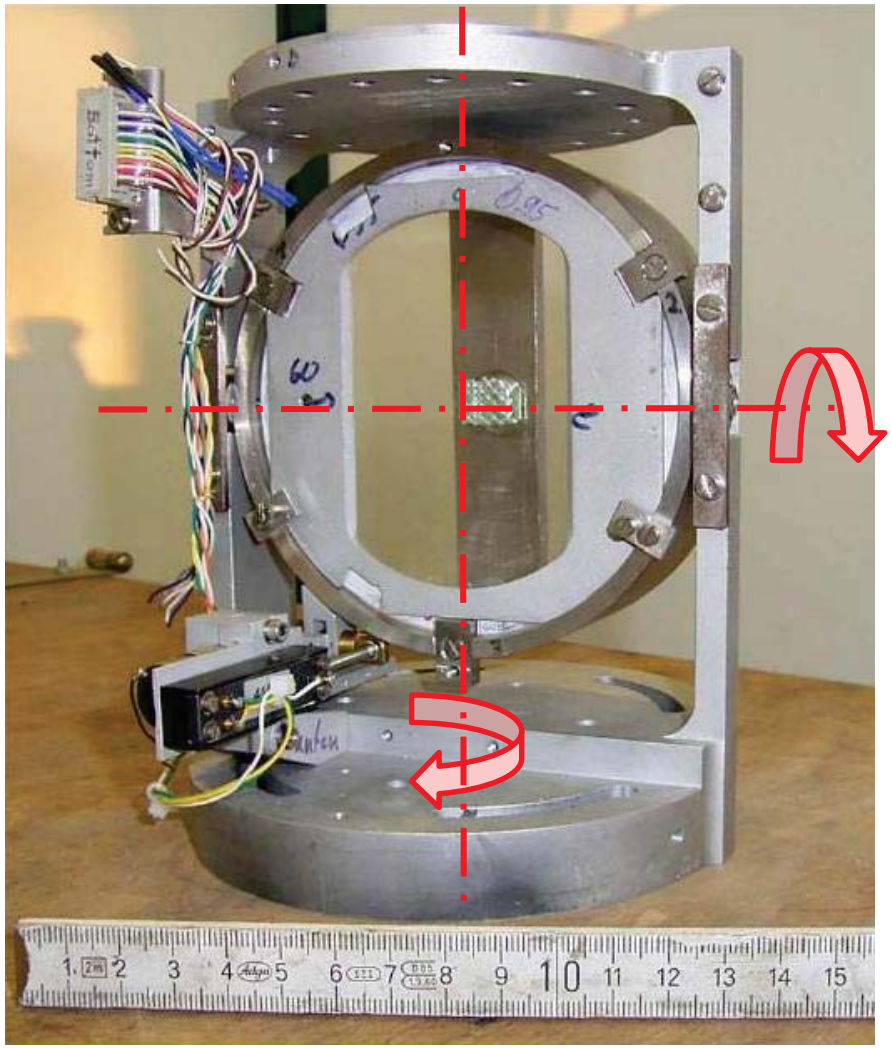


data normalized



SET-UP

BRAGG CRYSTAL



quartz (10-1)

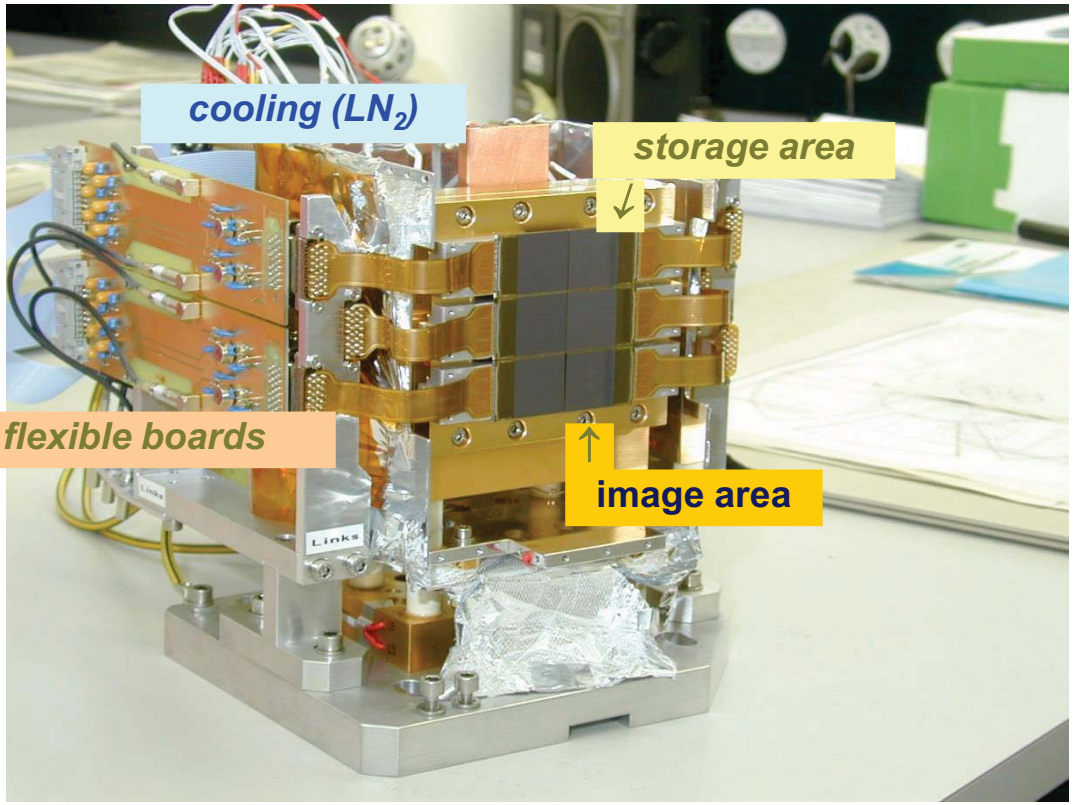
R_c = (2982.6±0.4) mm

quartz disk

thickness	*0.2 mm*
diameter	*10 mm*
attachment	*glueless*
support	*glas lense ϕ120 mm x 30 mm*

2-DIM. POSITION-SENSITIVE DETECTOR

2 × 3 charge-coupled device (CCD) array



x × y: 600 × 600 pixels each

pixel size 40 μm × 40 μm

frame transfer ≈ 10 ms
data processing 2.4 s

operates at – 100°C

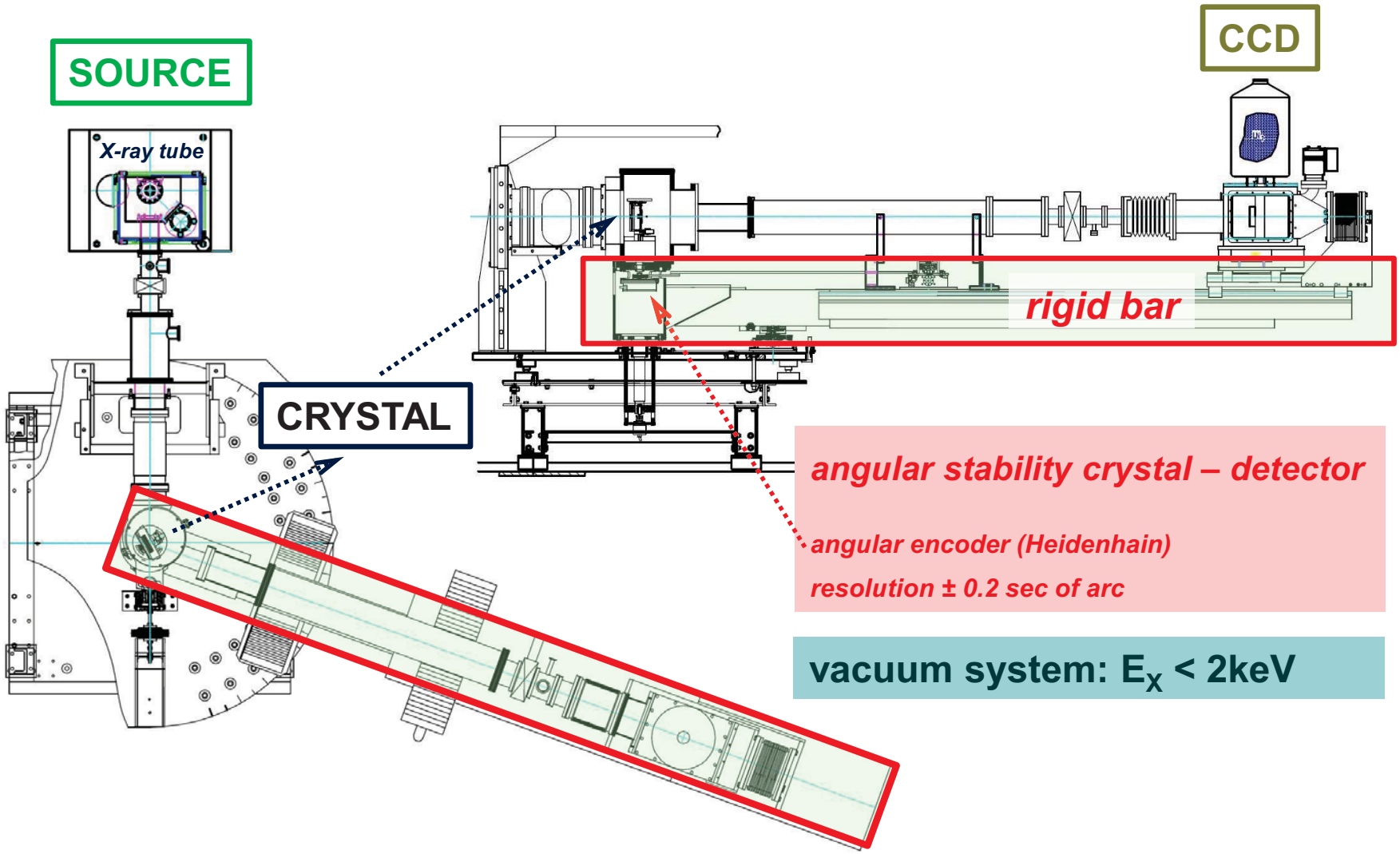
$\Delta E \approx 150$ eV @ 4 keV

$\varepsilon_{q.e.} \approx 90\%$

N. Nelms et al., Nucl. Instr. Meth. 484 (2002) 419

P. Indelicato et al., Rev. Sci. Instr. 77 (2006) 043107

MECHANICAL STABILITY



angular stability crystal – detector

angular encoder (Heidenhain)

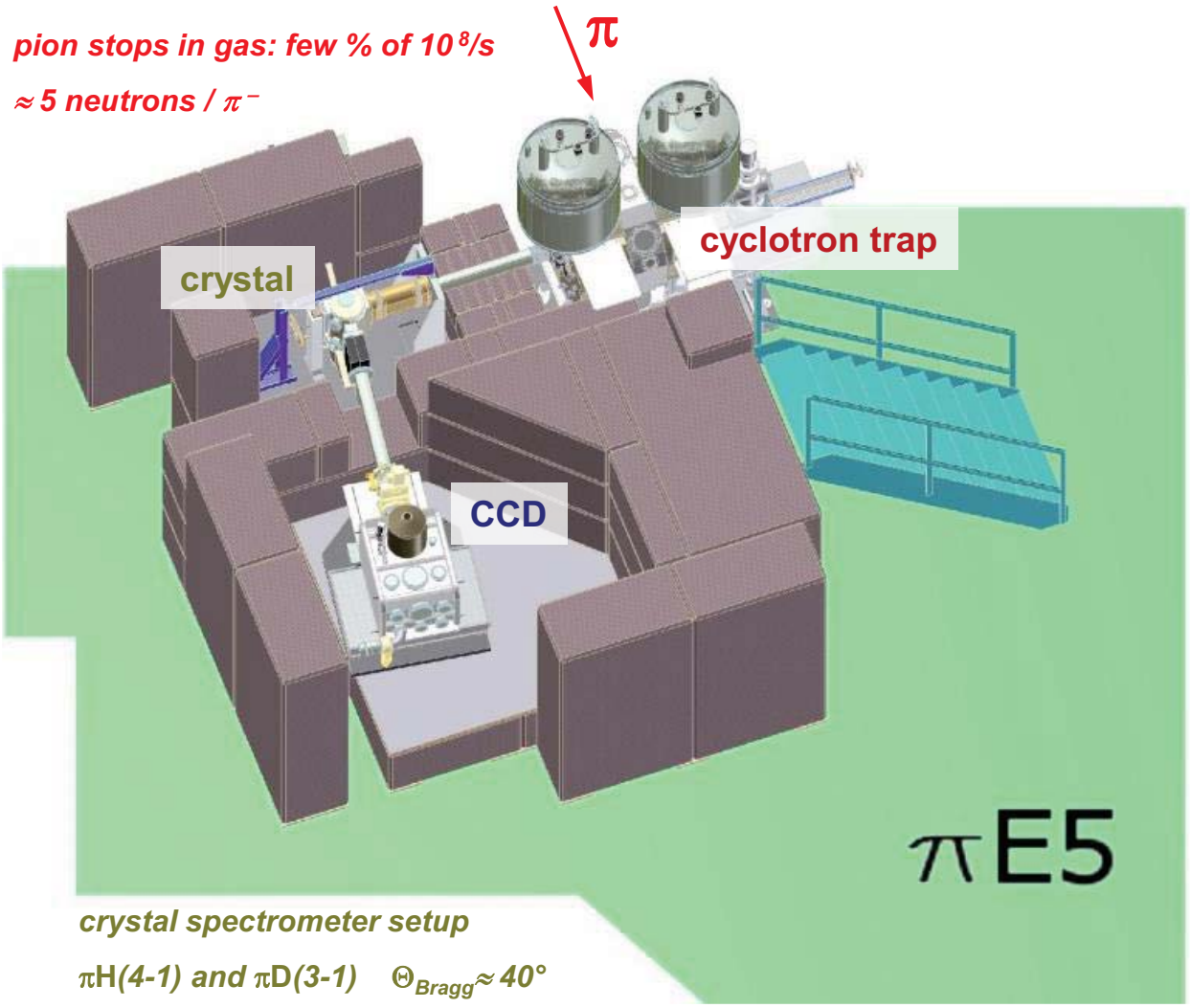
resolution ± 0.2 sec of arc

vacuum system: E_X < 2keV

PIONIC-ATOM SETUP (PSI)

pion stops in gas: few % of 10^8/s

≈ 5 neutrons / π^-

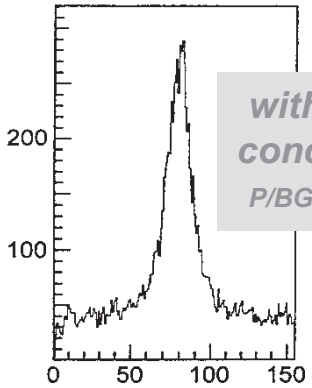


crystal spectrometer setup

πH(4-1) and πD(3-1) $\Theta_{Bragg} \approx 40°$

Th.Strauch et al., Eur. Phys. J. A 47 (2012) 88

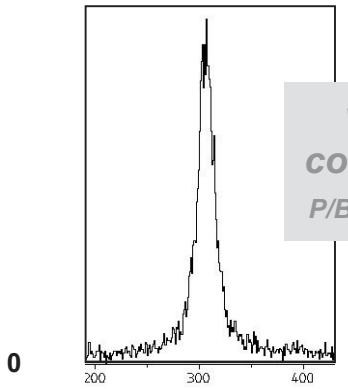
pionic hydrogen



without concrete

P/BG ≈ 7:1

peak/background x 10

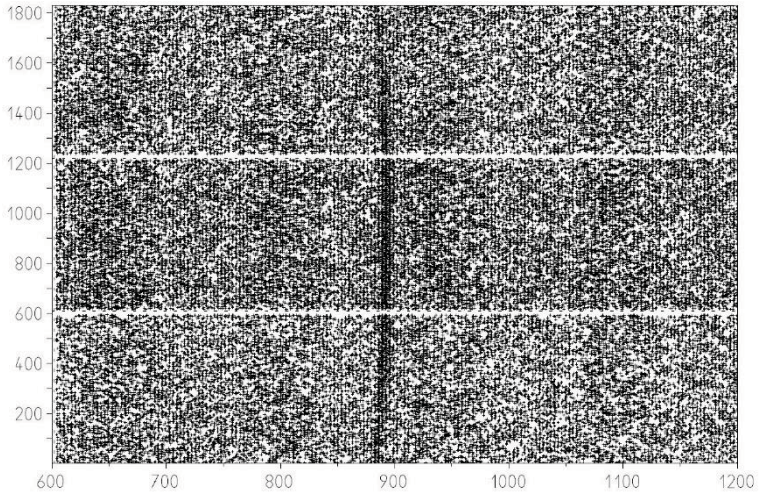


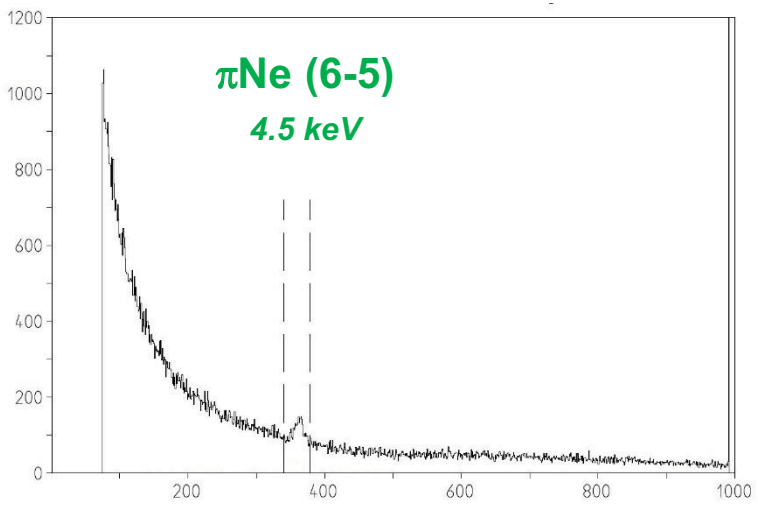
with concrete

P/BG ≈ 65:1

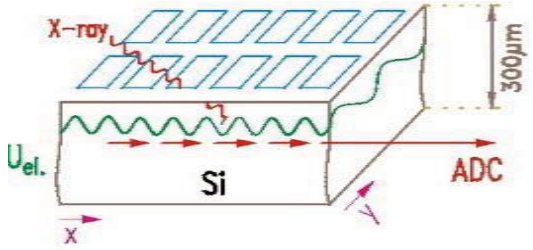
background reduction II

SPECIAL DEMANDS FOR EXOTIC ATOMS



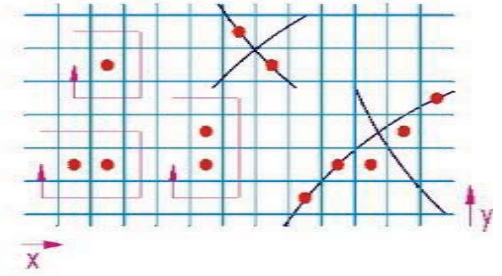


CCD = Charge–Coupled Device

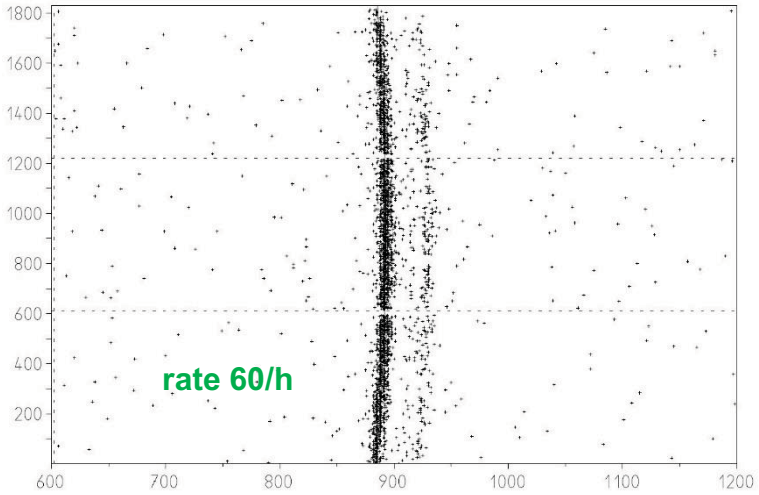


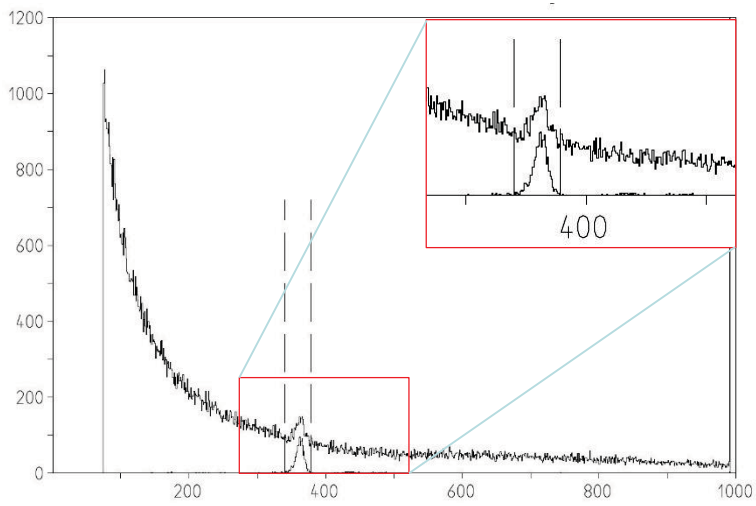
ΔE/E like Si(Li)

cluster analysis



SPECIAL DEMANDS - BACKGROUND SUPPRESSION





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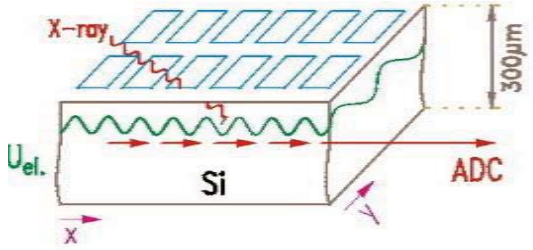

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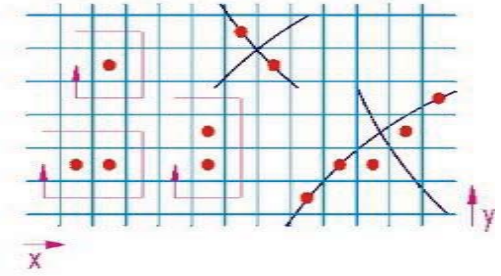
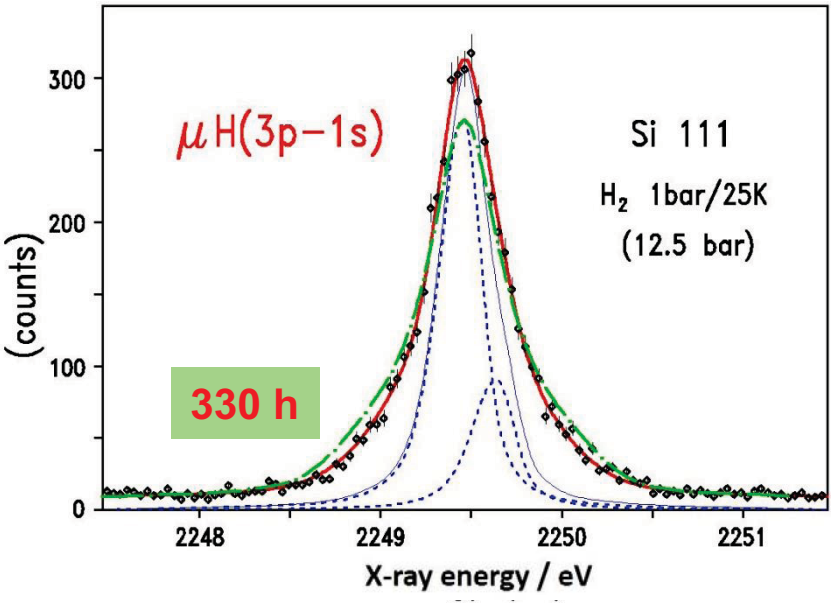
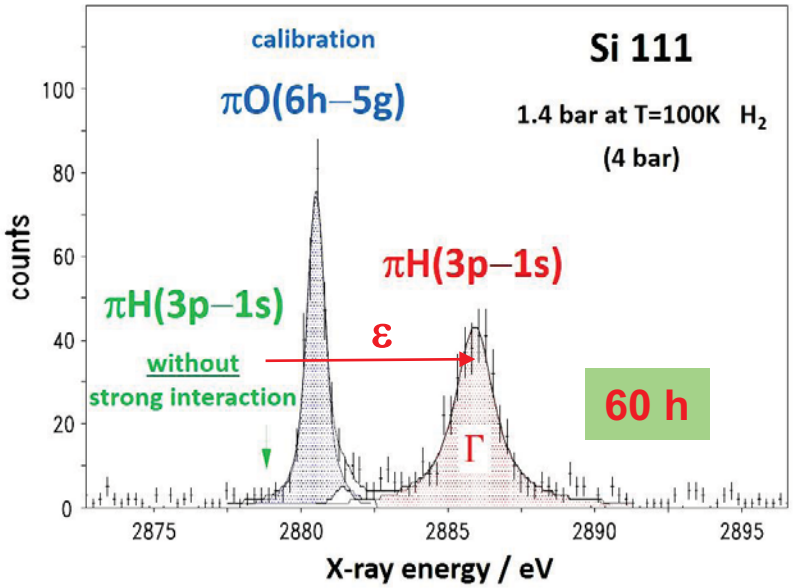


EXAMPLES

EXAMPLES – LINE WIDTH



D.S.Covita et al., Phys. Rev. Lett. 102 (2009) 023401



M.Hennebach et al., Eur. Rev. J. A 50 (2014) 190

Doppler broadening

(of nonresolved hyperfine doublet)

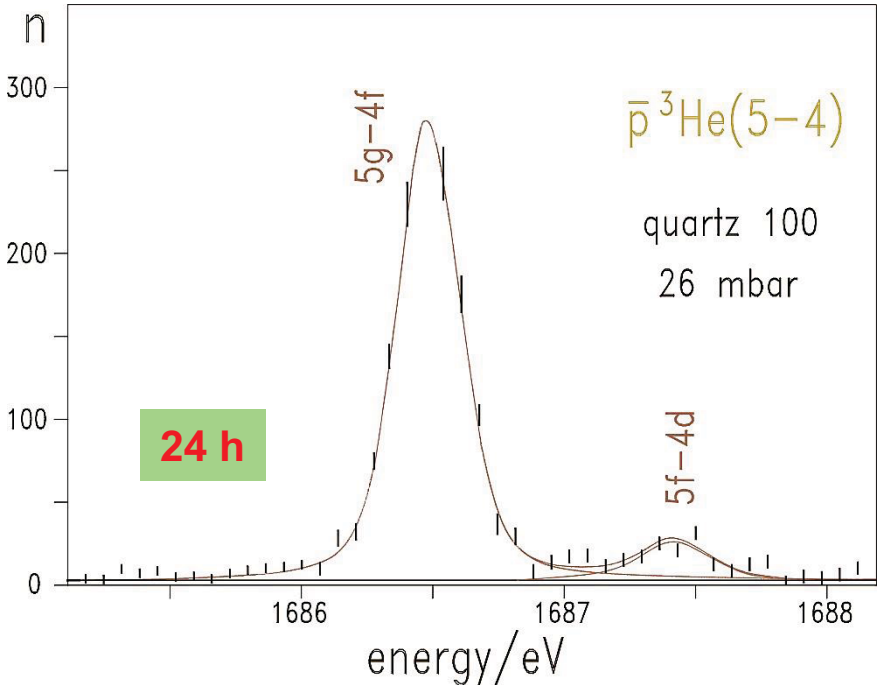
caused by high kinetic energies of μH

Hadronic shift ε

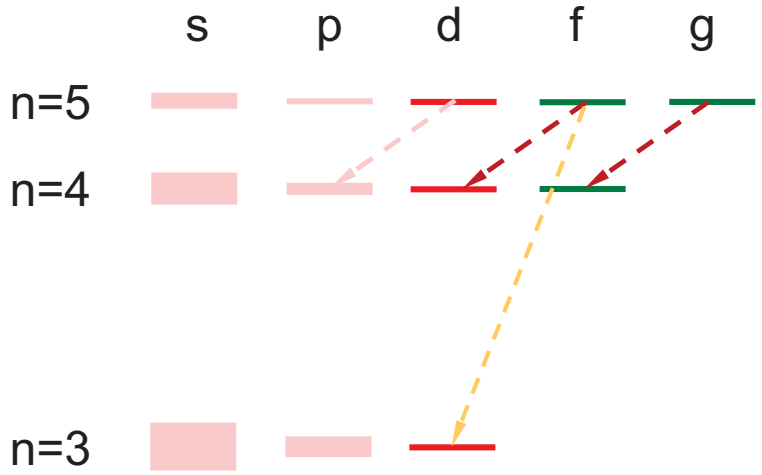
and broadening Γ

correction for Doppler broadening!

EXAMPLES - RESOLVING DETAILS



D. Gotta et al., Nucl. Phys. A 660 (1999) 283



$$\eta_{calculated} = 5.5 \cdot 10^{-7}$$

$$\eta_{measured} = (7 \pm 3) \cdot 10^{-7}$$

Intensity ratio $\frac{Y(5f-4d)}{Y(5g-4f)} = (7.7 \pm 0.6)\%$

Relative population $\frac{pop(5f)}{pop(5g)} = (21 \pm 2)\%$

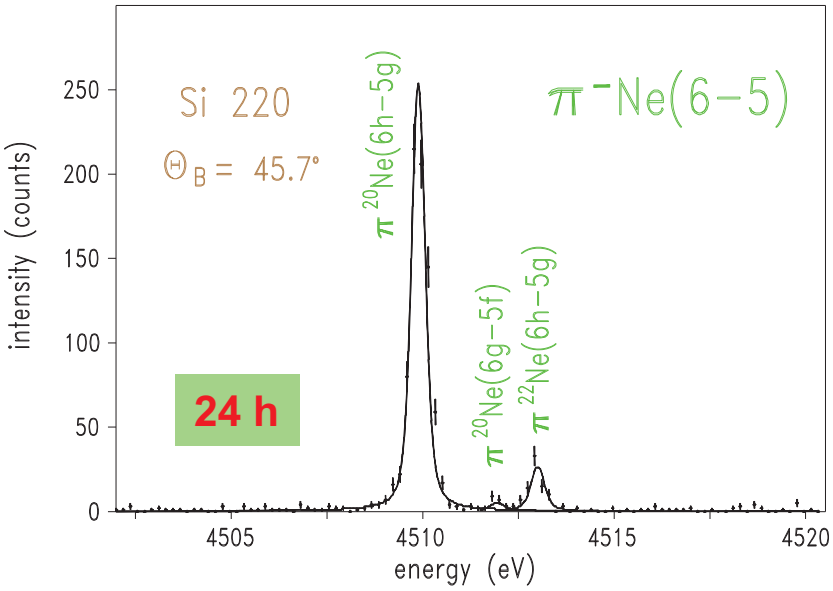
EXAMPLES - ENERGY STANDARDS

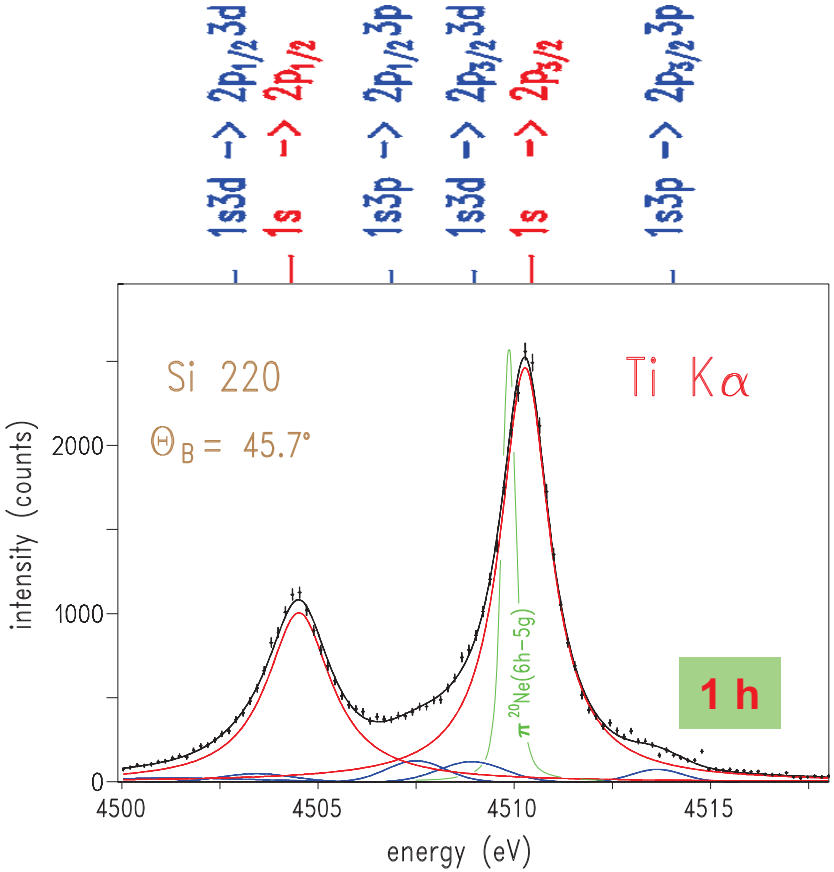
connect exotic- and electronic-atom X-rays

QED

πNe (6h-5g)

(4509.894 ± 0.001) eV



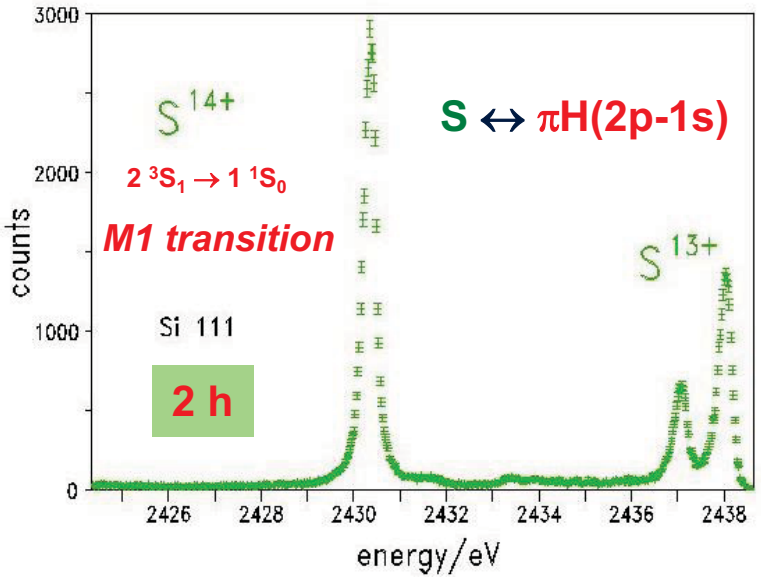


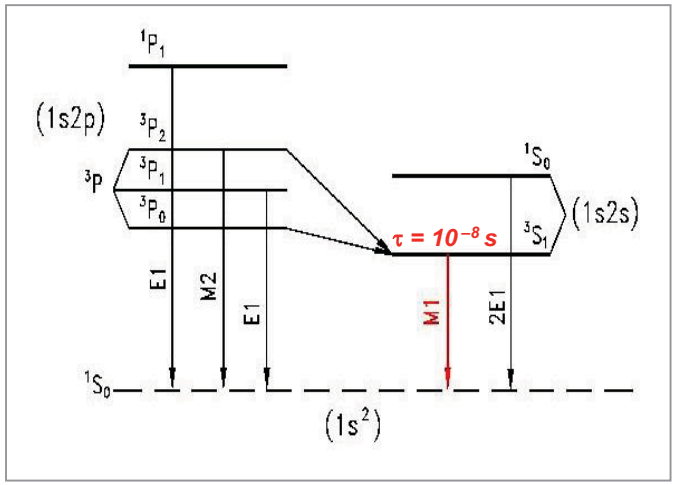
D.F.Anagnostopoulos et al., Phys. Rev. Lett. 91 (1999) 2018

EXAMPLES - FEW ELECTRON ATOMS

Electron-cyclotron resonance ion trap: 30000 events in line

S. Biri, L. Simons, D. Hitz et al., Rev. Sci. Instr., 71 (2000) 1116
K. Stiebing, Frankfurt – design assistance



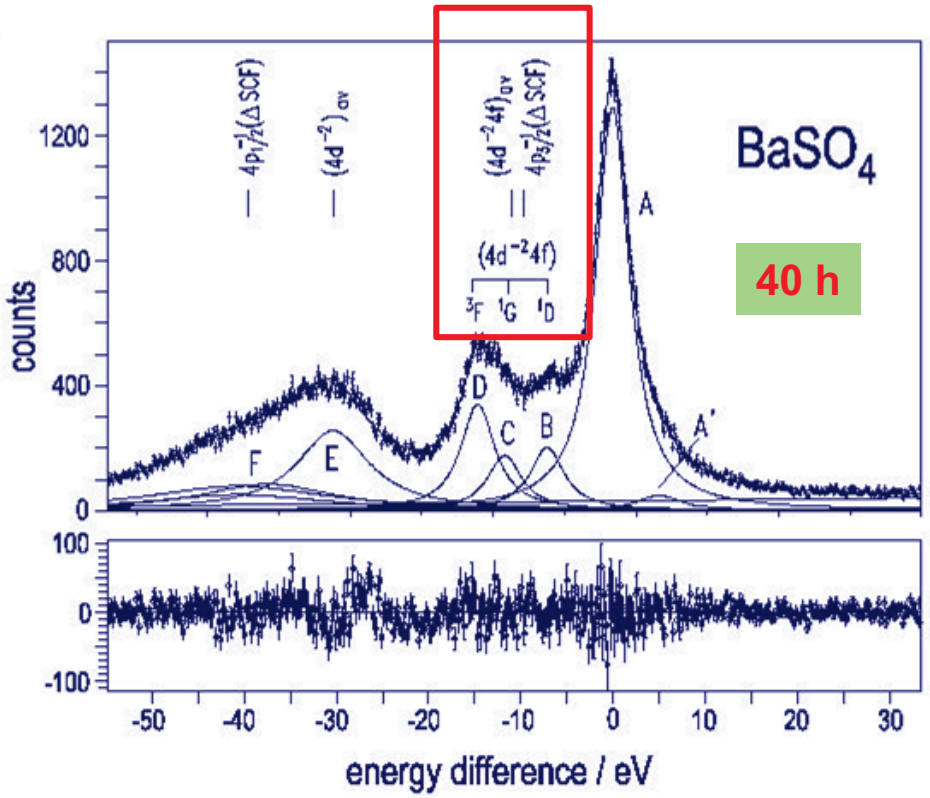


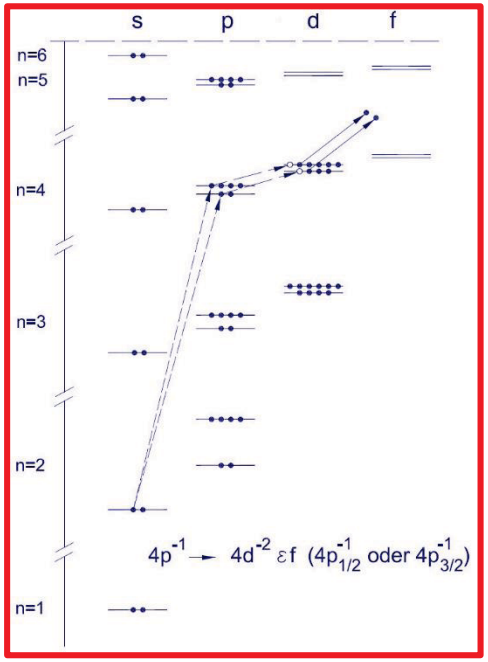
RESOLUTION FUNCTION	*D.F.Anagnostopoulos et al., Nucl. Instr. Meth. B 205 (2003) 9* *D.F.Anagnostopoulos et al., Nucl. Instr. Meth. A 545 (2005) 217*
Few keV X-ray standards	*S.Schlesser et al., Phys. Rev A 88 (2013) 022503*

EXAMPLES - Ba $L\gamma_{2,3}$ (2s → 4p region)

Simultanuous measurement of ΔE ≈ 100 eV

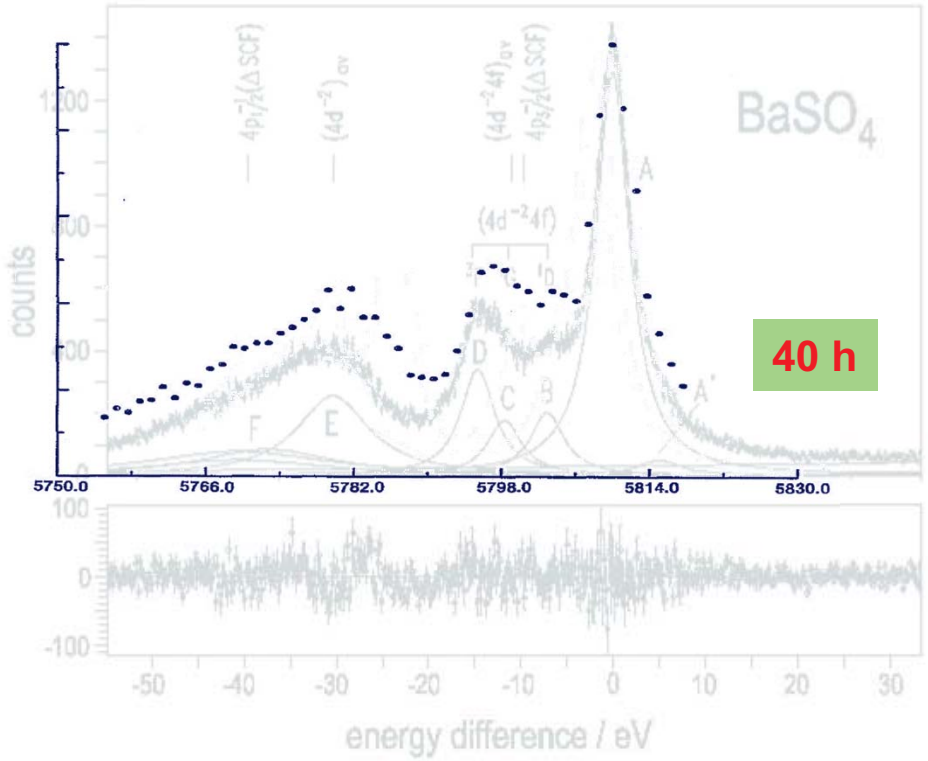
≈ 50.000 events in ≈ 40 h





Th. Strauch, diploma thesis, Univ. Siegen and IKP , FZ Jülich (2005)

EXAMPLES - Ba $L\gamma_{2,3}$ (2s $\rightarrow$ 4p region)



40 h

Step scanning with 2-crstal setup

≈ 5.000 events

M.Ohno and R.E.LaVilla,, Phys. Rev. B 39 (1989) 8845

EXAMPLES - CHEMICAL EFFECTS

More X-rays

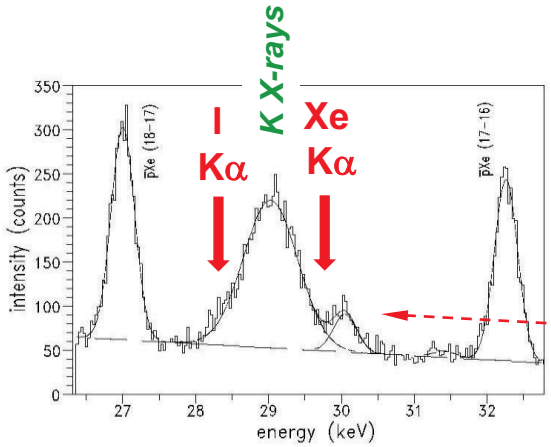
Kα X-ray emission in manganese compounds

*Talk by **M. Jabua**, Tuesday OP42 15:40*

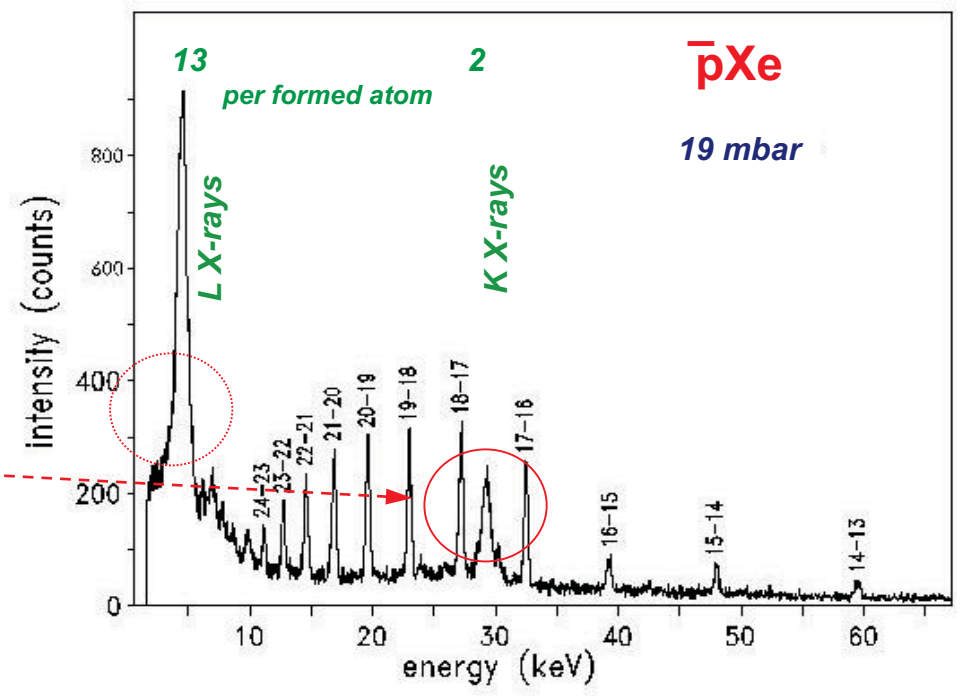
instead of a SUMMARY - one (of several) dream(s)

ELECTRONIC & ANTIPROTONIC X-RAYS - XENON

many remaining electrons



many unresolved lines ?



data: PS175 Ar, Kr, Xe
Reanalysis: D.G., K.Rashid, B. Fricke, P. Indelicato, L.M. Simons, Eur. Phys. J. D 47 (2008) 11

- *high resolution spectroscopy with crystal spectrometer*
- *coincidence experiments X-rays / Auger electrons*

DATA FROM EXPERIMENTS

	collaboration		*measurements*	
$\bar{p}$	**PS 207**	**CERN**	**antiprotonic atoms**	**1994 – 1996**
	R-94.01	**PSI**	**π / μ mass ratio**	**1994 – 1997**
	R-97.02	**PSI**	**pion mass**	**1999 – 2000**
μ/π	**R-98.01**	**PSI**	**pionic hydrogen**	**2000 – 2006**
		PSI	**muonic hydrogen**	**2004**
	R-06.03	**PSI**	**pionic deuterium**	**2006**
X-rays		**FZJ**	**electronic X-rays**	**2006 – 2014**

Coimbra, Debrecen, Ioannina, FZ Jülich, Leicester, Neuchatel, LKB Paris,PSI, Tbilisi, SMI Vienna, ETH Zürich

THANK YOU